The Use of Radar to Improve Rainfall Estimation over the Tennessee and San Joaquin River Valleys

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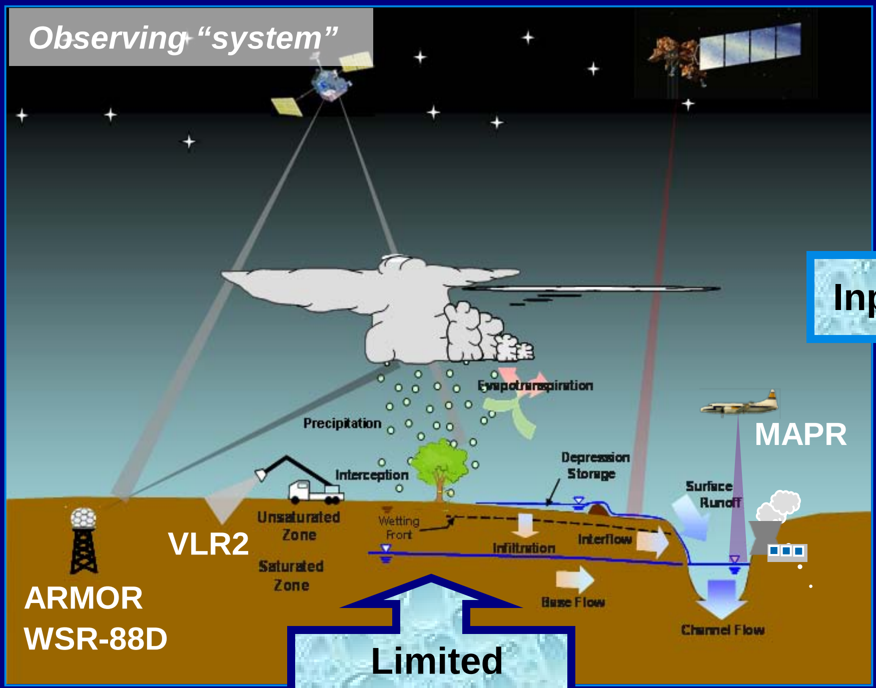
•*Remote Sensing of the Water Budget*

Where is the water and how much is there?

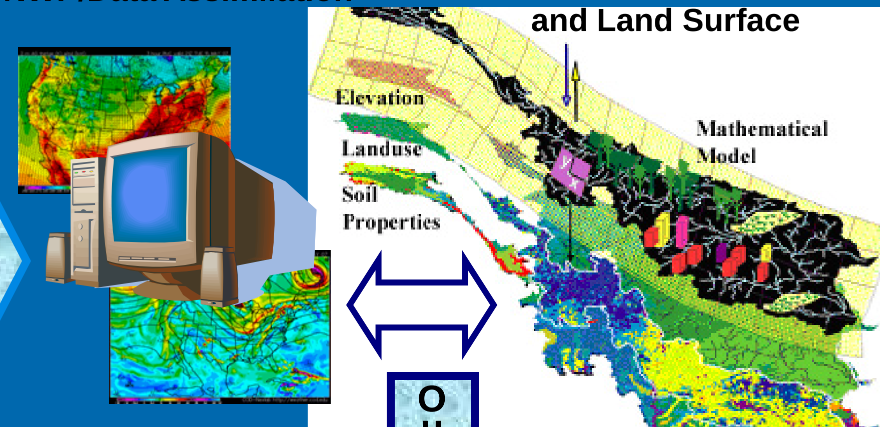


Limited Investment

•*Coupled Modeling: Diagnostic and Prognostic*

Where is it going today, where will it go tomorrow?

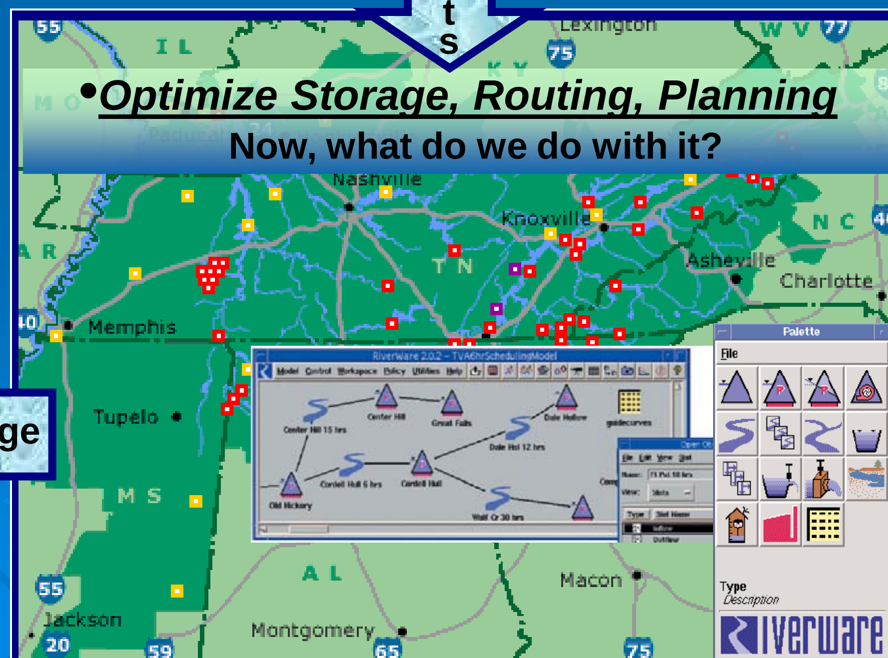
Inputs



Outputs

•*Optimize Storage, Routing, Planning*

Now, what do we do with it?



Manage

•*Overarching Motivation and The Result*

✓ **Improved Water and Energy Management**

Outline

- Overview collaborative radar rainfall project between Tennessee Valley Authority (TVA), VCSI (The Von Braun Center for Science & Innovation), NASA MSFC and UAHuntsville
  - **AREPS: ARMOR Rainfall Estimation Processing System**
    - Demonstration project of real-time radar rainfall using a research radar
  - **NREPS: NEXRAD Rainfall Estimation Processing System**
    - Expansion to Tennessee River Valley using operational WSR-88D
  - Objectives, methodology, some results and validation, operational experience and lessons learned.
- NASA Earth Science – Applied Science Program's ARRA Project: Water Supply and Management in California
  - NASA MSFC and UAHuntsville to provide NREPS rainfall input to NASA MSFC/USRA distributed hydrological model for soil moisture and evapo-transpiration estimation.
  - NREPS challenges, ongoing/future work and opportunities over Central CA and beyond.

Objective and Motivation

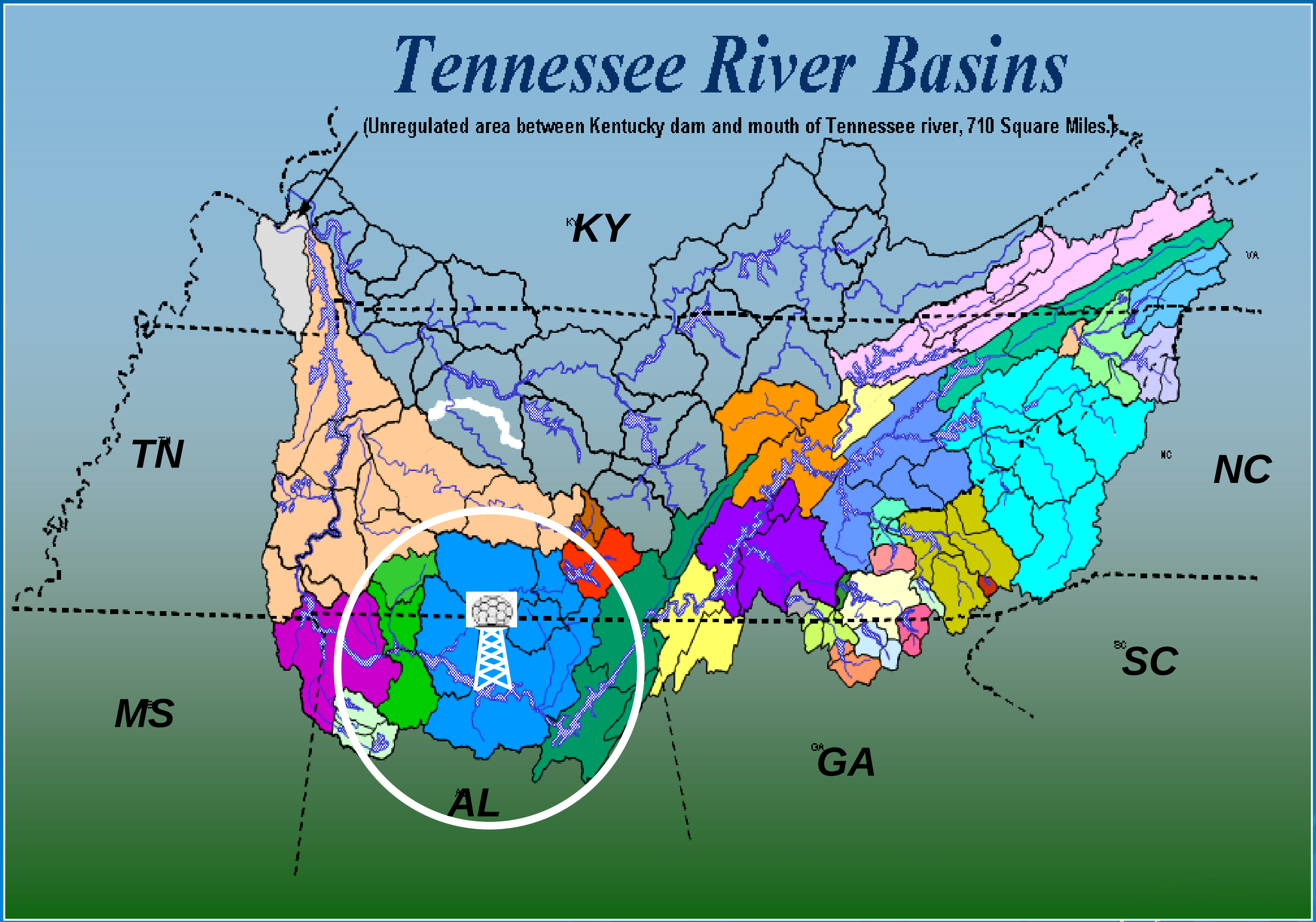
- TVA River management and distributed rainfall measurements- reducing dependence on rain gauges.
  - Provide custom-tailored, radar-based rainfall products specific to TVA's operational river management needs (e.g., 6-hr sub-basin mean rainfall)
  - Potential reduction of costs associated with maintenance of large TVA rain gauge network
- *Research & Development → Operations*

TVA River Forecast Center

http://www.tva.com/river/flood/center.htm

- Knoxville, TN: staffed around the clock and 365 days a year
- River management duties include
  - Issuing forecasts of reservoir levels and water releases at TVA dams
  - Providing hourly generation schedules for TVA hydroelectric projects
  - Providing special notifications to the public during flood events
  - Evaluating cooling water needs for TVA coal-fired and nuclear plants
  - Monitoring water quality conditions below TVA dams (oxygen levels)
  - POC in event of a river system emergency
- Complex, interdependent and sometimes conflicting set of river management requirements and responsibilities.
  - Forecasters are busy! **They need reliable data for decision making**.
- Forecasters use lumped hydrologic runoff model tuned to parameters and input data performance, including gauge rainfall mapped to sub-basins using Theissen polygons.

Tennessee River Watershed



- TVA River Scheduling Division
- 112 sub-basins
- 1840 km^2
- 189 rain gauges maintained by TVA
  - Annual costs: $6K / gauge

Demo project using ARMOR

Objective:

Transition from rain gauge (point) estimation paradigm to radar (distributed) measurement

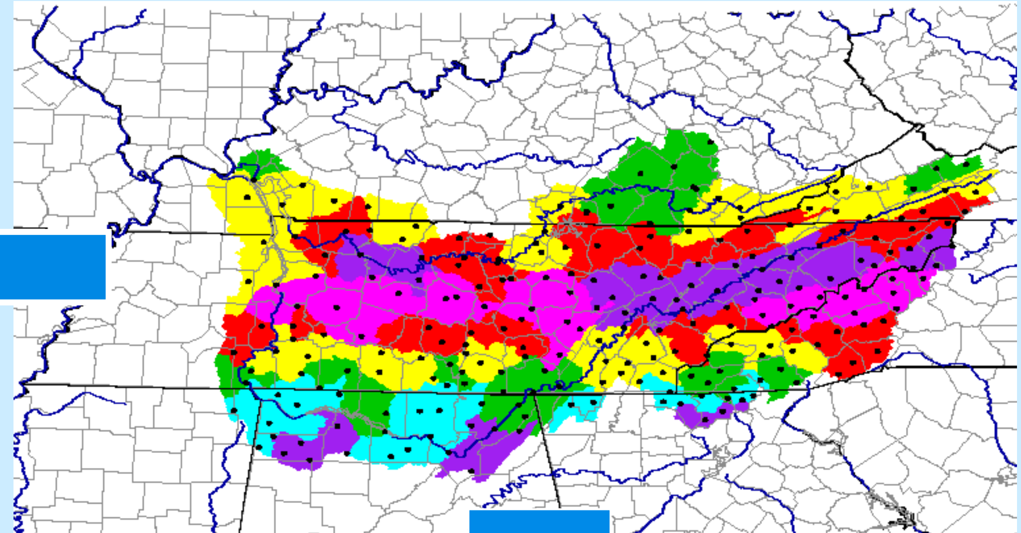
CURRENT River Operations Gauge Rainfall Inputs

Advanced Radar, QPE Applications

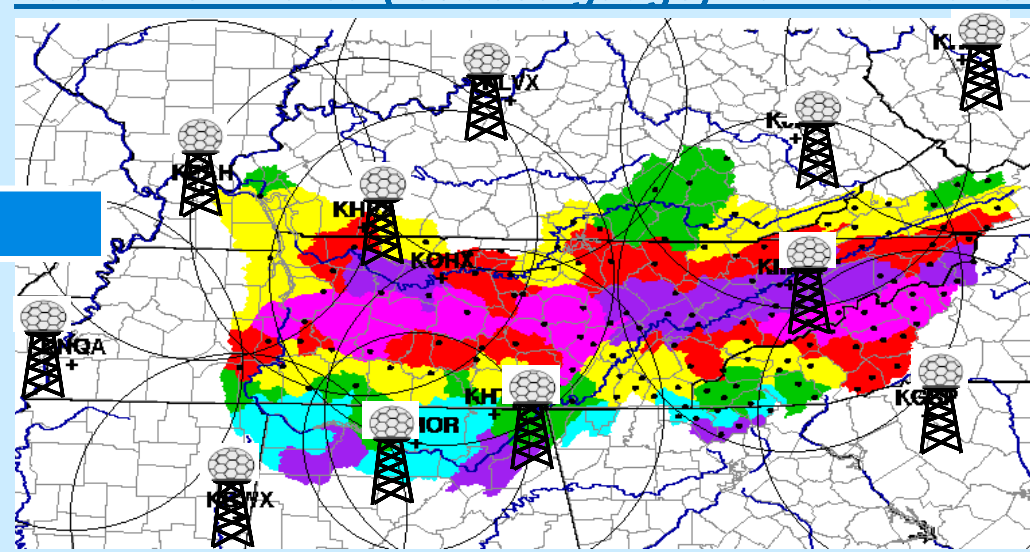
FUTURE TVA

River Ops Rainfall Inputs

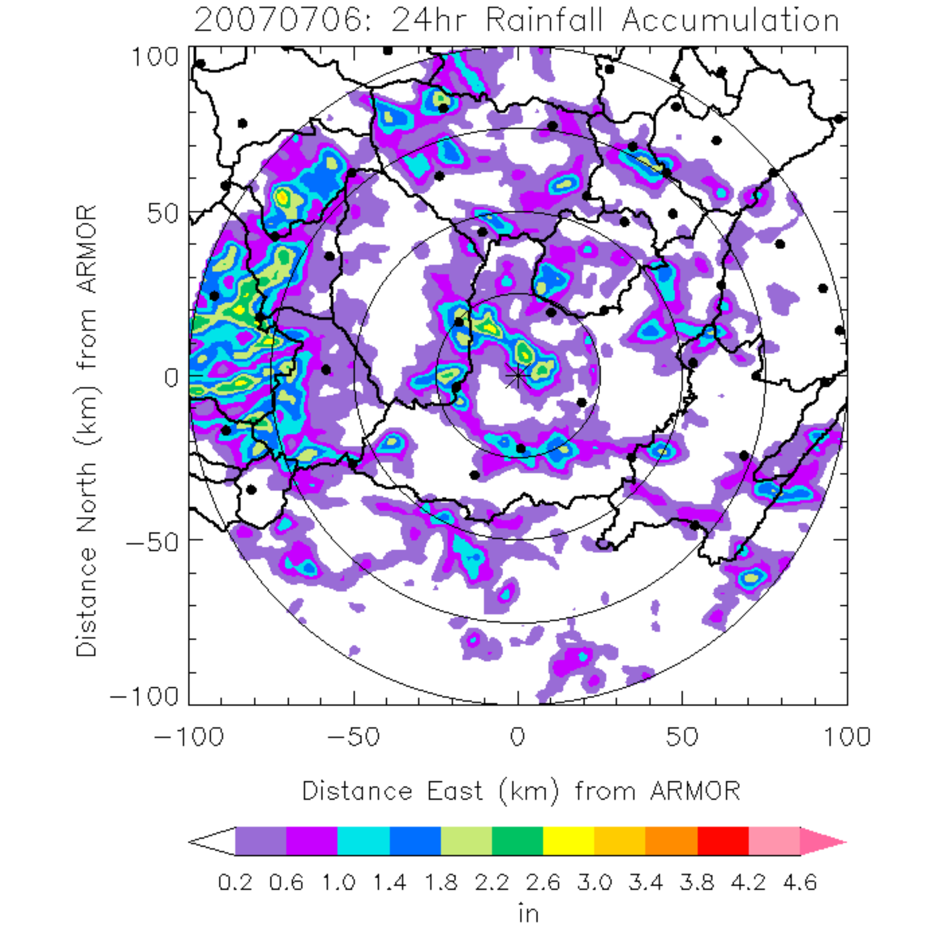
Rain Gauge-Dominated Rain Estimation



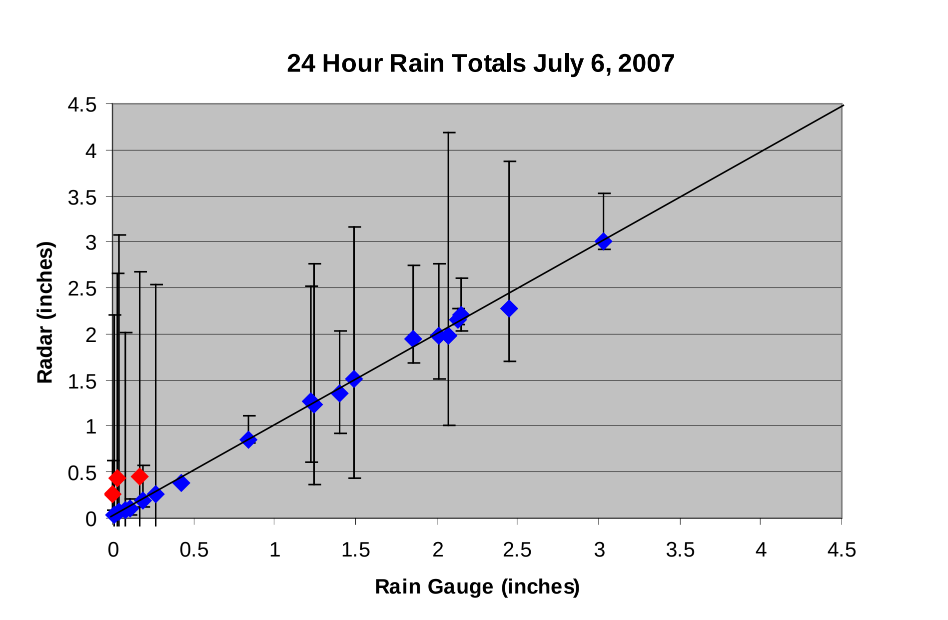
Radar-Dominated (*reduced gauge*) Rain Estimation



Point (gauge) vs. areal (radar) rainfall estimates

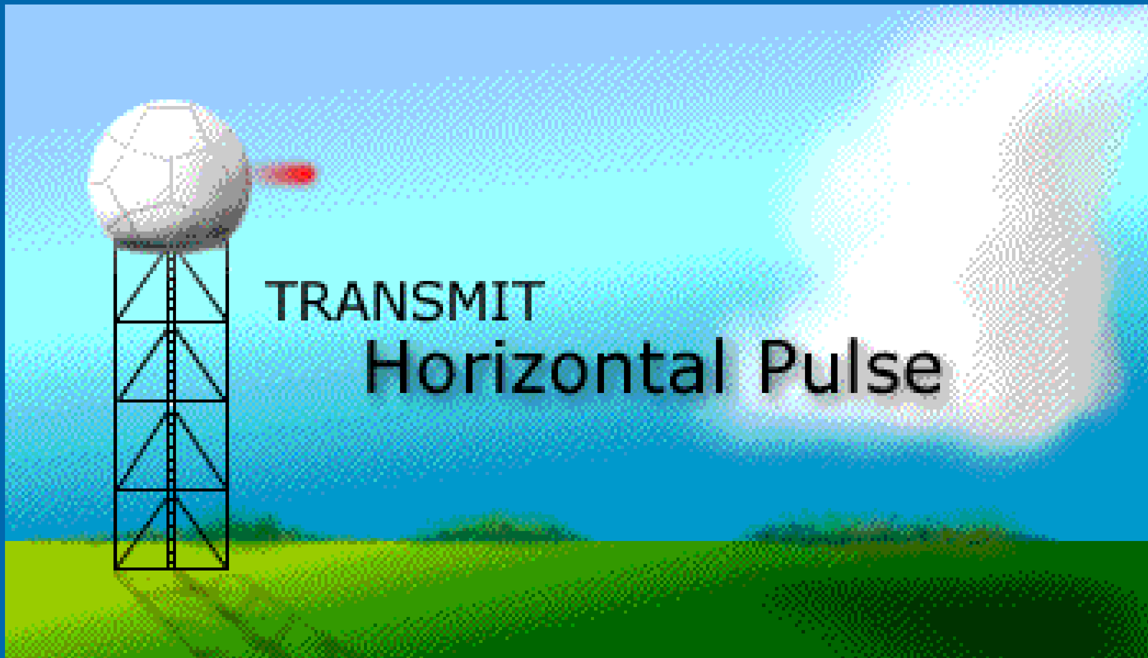


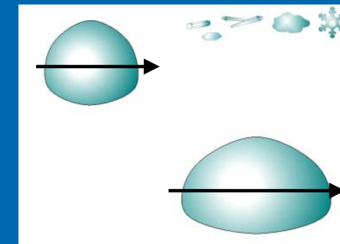
- E.g., Warm season precipitation event
- Favorable comparison to gauges- (points)



- BUT much of the heaviest precipitation missed at individual gauges (this is fairly typical)!
- Heterogeneity of rain field presents problems for point measurements, even for gauge-adjusted radar maps

Conventional Radar *Estimates* of Precipitation



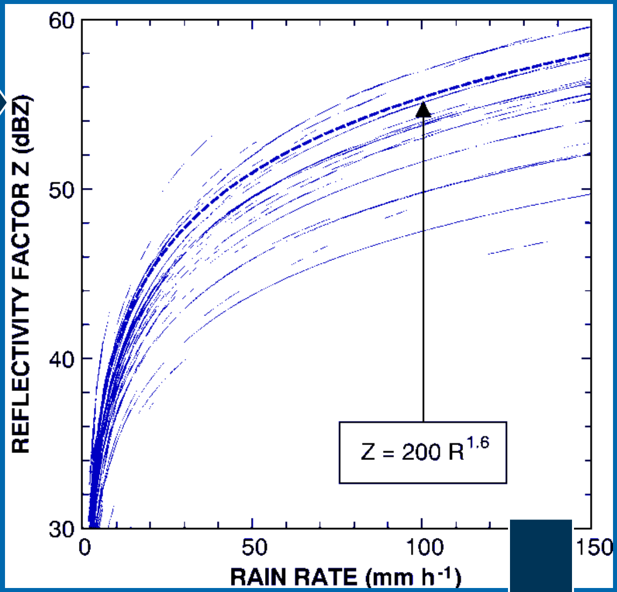


- Raindrops (often the target) are deformed by drag as they fall.
- Become more oblate with size (diameter)

- Radar scans rain/precipitation by sending out a series of microwave pulses along a 1º beam while sweeping that beam through a 360º circle.
- Executed for several elevation angles and repeated every 5 – 6 minutes.
- Returned power from rain (called reflectivity- "Z") is typically measured at only one polarization (e.g., horizontal) and related to rainfall via "Z-R" power laws: $Z = aR^b$

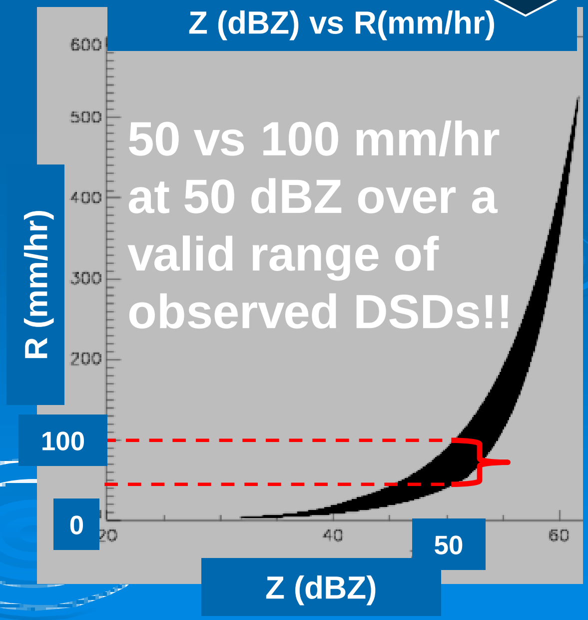
QPE: Problem with conventional radar-rainfall approaches: Reflectivity Factor (Z) - Rainfall Rate (R) Relations

- **Problem: Numerous rainfall-reflectivity relationships, which one is correct?**
- **Random error up to 100% (instantaneous) can occur. Typical space-time smoothing reduces to say 20%-40%.**
- **Measurement sensitive to *rain drop size distribution*, *presence of hail/ice/snow*, and *radar calibration*.**
- ***Without care*, unacceptable errors/bias can be incurred for high resolution hydrological applications.**
- **Even gauge corrections are still beholden to gauge calibration/error/sample mismatch- a problem at times (more often then we would like to admit).**



Sample of current operational relationships:

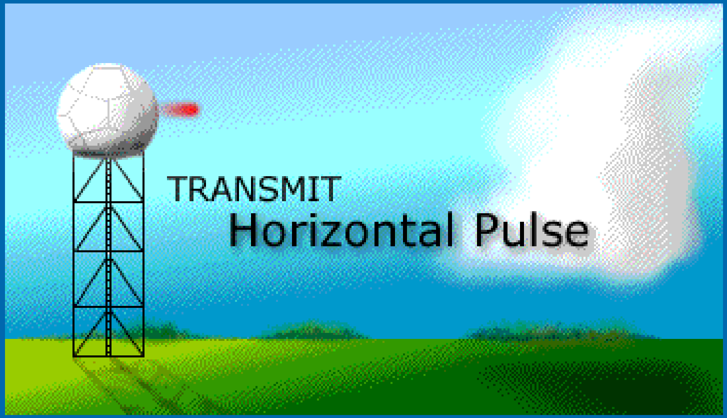
$Z = 300 R^{1.4}$ - convective rain
$Z = 250 R^{1.2}$ - tropical rain
$Z = 200 R^{1.6}$ - summer stratiform rain
$Z = 130 R^{2.0}$ - winter stratiform (eastern US)
$Z = 75 R^{2.0}$ - winter stratiform (western US)

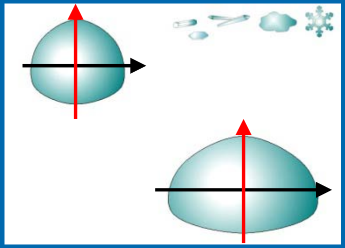


How do we correct these issues?

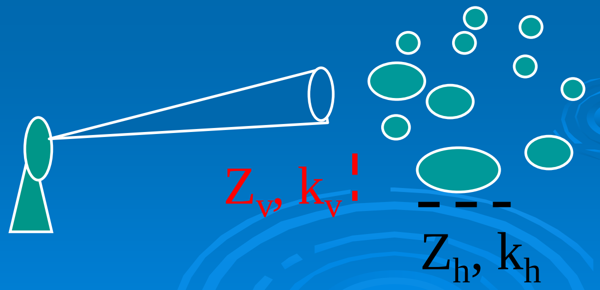
Enter Dual-Polarimetric Radar

- **Approach:** Provide measurements in both horizontal and vertical polarizations (dual-polarimetric).
- **Advantages:** Better description of various particle types/shapes in a given volume
- Determine size distribution- more accurate rain rates (**improved QPE**)
    - Rain drop shape related to size
- **Hydrometeor ID** (hail vs. rain) and non-meteorological scatterers (clutter!)
- Consistent **calibration**





We need the measurement in H and V directions!



Enter Polarimetric Radar

And more variables……..

1. **Reflectivity factor Z at horizontal (Z_h) or vertical (Z_v) polarization [Conventional radar measure]**

   - Measure of **drop size and concentration;**

     - Most sensitive to drop **SIZE** (D^6)

2. **Differential reflectivity Z_{DR} (Z_h/Z_v)**

   - Measure of median drop diameter→ **SIZE/SHAPE**

   - Useful for rain / hail / snow discrimination→ **SIZE/SHAPE**

3. Specific propagation **differential phase K_{DP} $\Sigma(k_h - k_v)$**

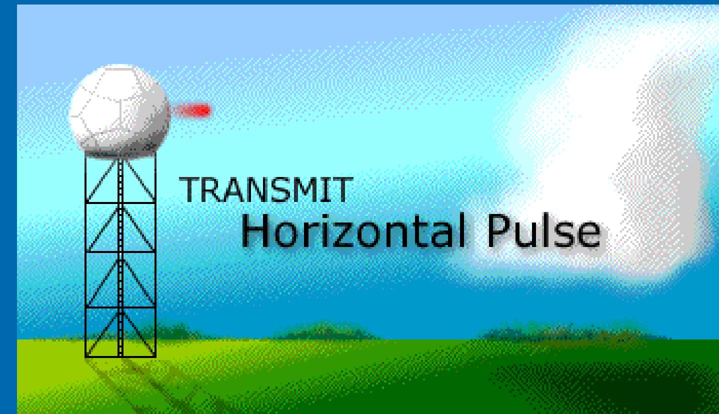
   - Measure of water content and drop size→ **NUMBER/SHAPE**

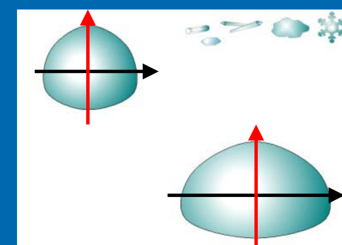
   - Immune to radar calibration, attenuation, partial beam blockage

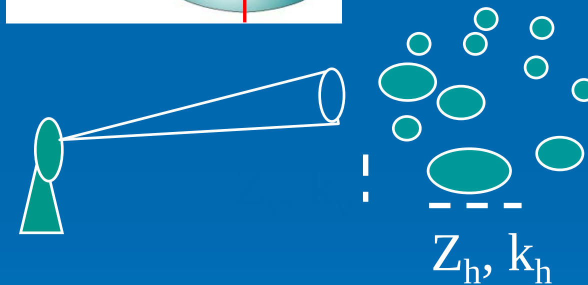
4. **Correlation coefficient ρ_{hv}**

   - Indicator of mixed precipitation → **SHAPE/PHASE/CANTING (Depolarization)**

   - Useful for identifying non-meteorological scatterers too!







Advantages: Better description of various particle types/shapes in a given volume

- Determine size distribution- more accurate rain rates (**improved QPE**)
- **Hydrometeor ID** and non-meteorological scatterers (clutter!)
- Consistent **calibration**

Dual-Polarimetric Radar: Improved QPE through improved description of particles

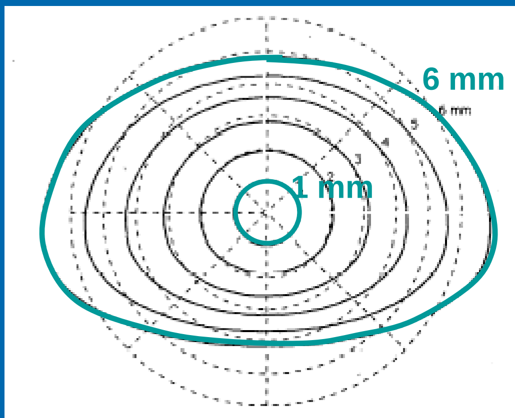


FIG. 7. Computed shapes for d = 1, 2, 3, 4, 5 and 6 mm with origin at center of mass. Shown for comparison are dashed circles of diameter d divided into 45 degree sectors.

Rain is Oblate

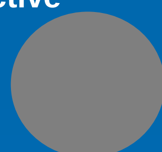
Small Drops (1 mm)

Large Drops (> 4 mm)

Axis ratio decreases with increasing size- more oblate

Hail/Graupel

Radar "sees" an effective sphere



Axis ratio ~ 1

Tumbling and lower dielectric strength makes hail look like spheres

Unless they start to melt…

Melting Hail/Graupel (Toroid or ice core; looks like a huge drop)

Axis ratio < 1

Assessing size and Shape with Dual-Pol

Particle Size-Controlled

Smaller ZDR → Larger ZDR

Smaller Z → Larger Z

Small Drops	Large Drops
Rain	Insects
Hail/Graupel	Rain

Smaller KDP → Larger KDP

Number Concentration Controlled

Smaller # → Larger #

Larger ZDR → Smaller ZDR

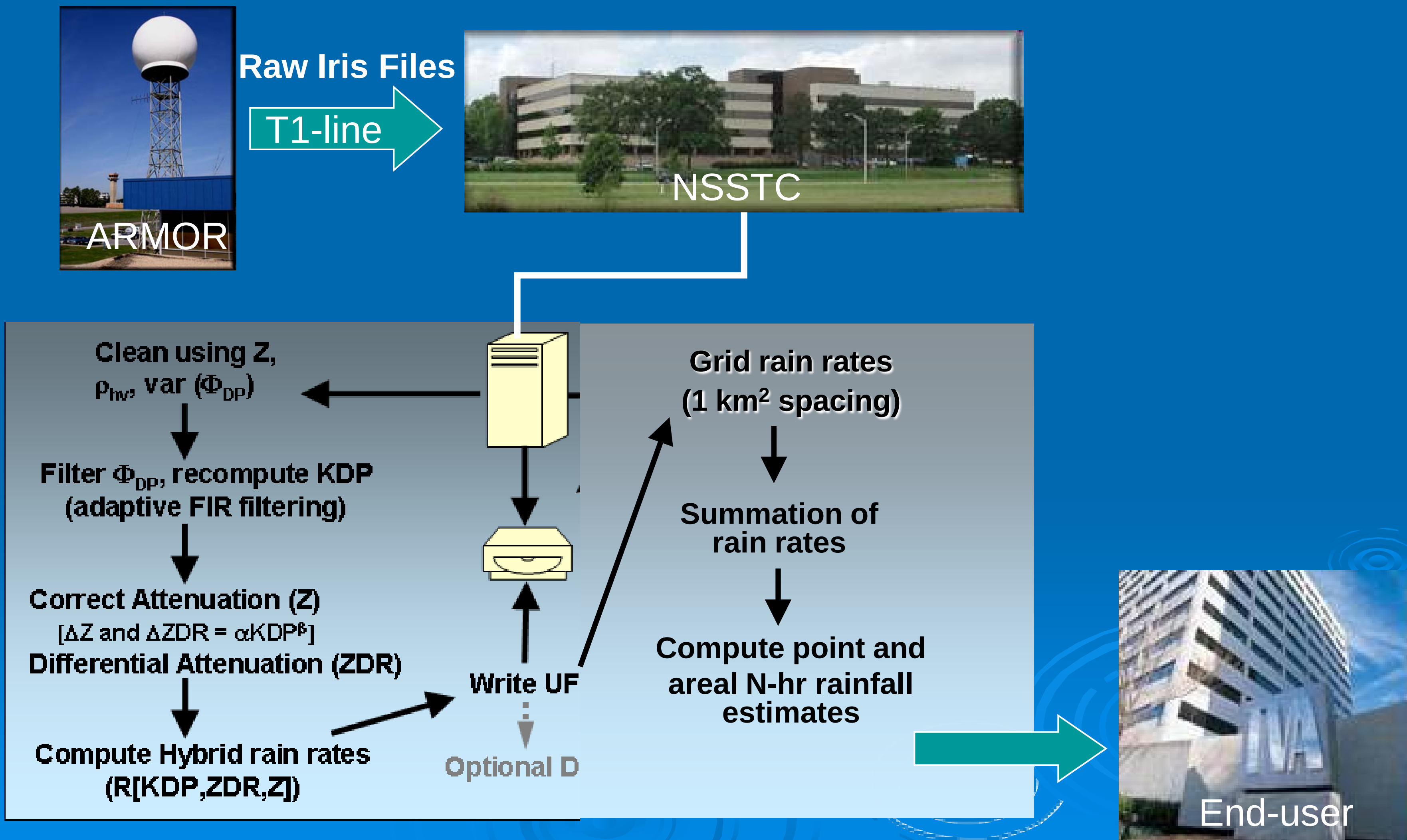
Large Drops VS **Small Drops**

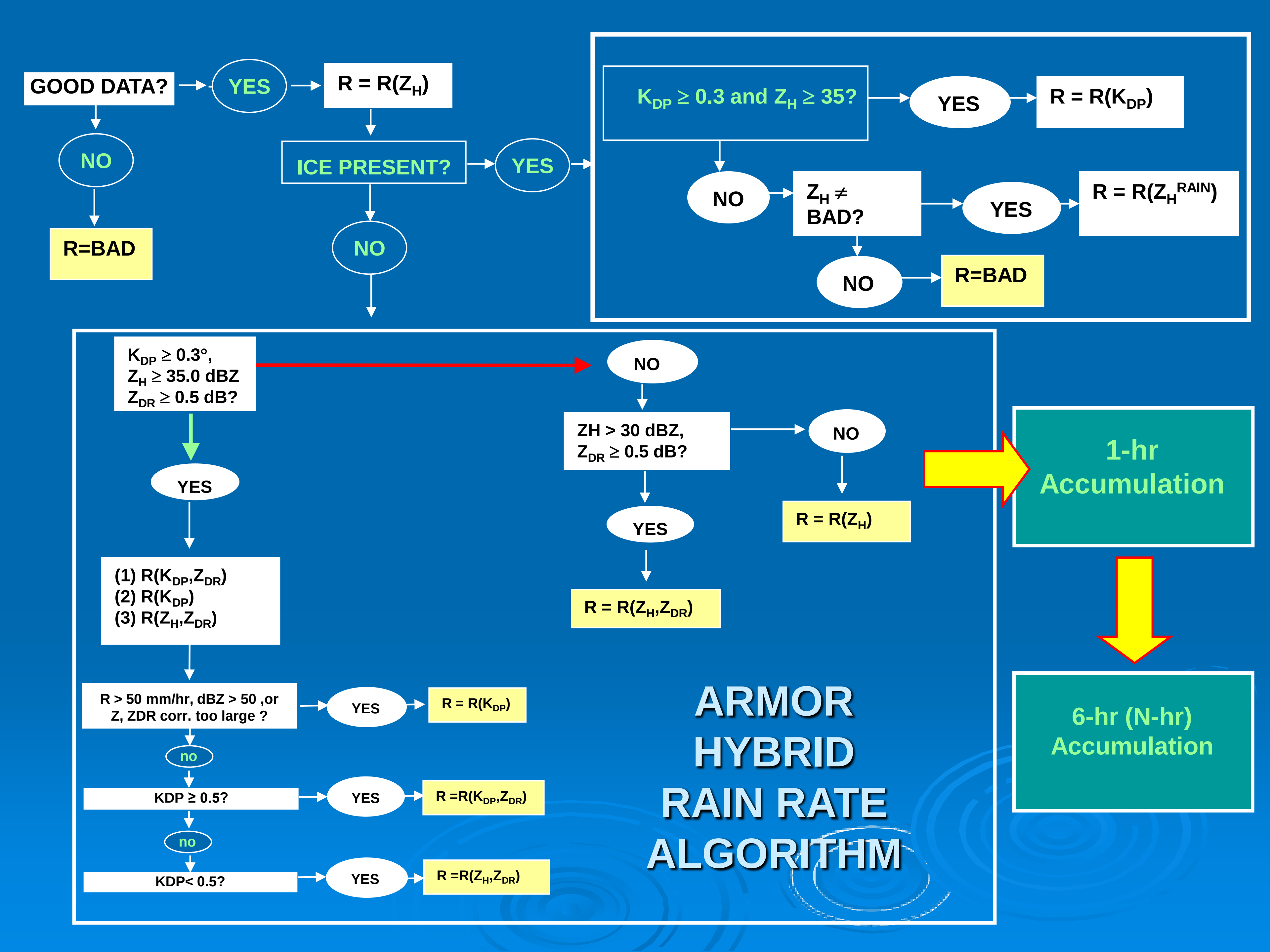
Smaller KDP → Larger KDP

Advanced Radar for Meteorological & Operational Research

- Location:
  - Huntsville International Airport, Huntsville, AL (Altitude 206m)
- C-band *dual-polarimetric* Doppler radar
- Simultaneous transmit and receive of H, V
- Variables: Z, V, W, ZDR, Φ_{DP}, ρ_{hv}
- Operations:
  - 24-hrs a day / 7 days
  - Rain volumetric scans at least every 5-min (tilts: 0.7°,1.5 °,2.0 °)
  - Also used in research mode (e.g., RHIs, full volumes, vertically pointing scans)
- Routine calibration:
  - Receiver calibrations
  - Solar scans
  - Self-consistency amongst variables
  - Comparisons with TRMM and rain gauges

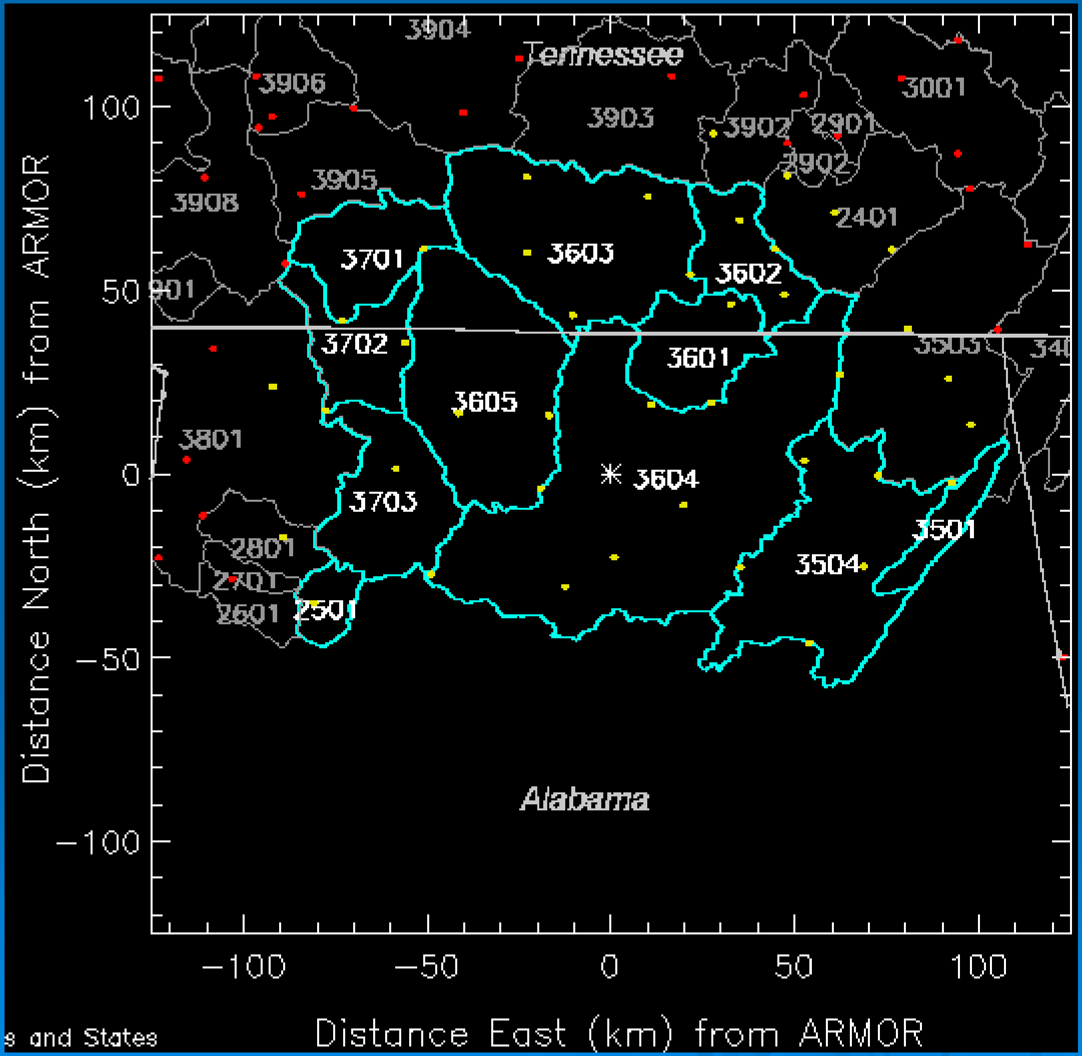
ARMOR Rainfall Estimation Processing System (AREPS)





GOOD DATA?
YES
R = R(Z_H)
NO
R=BAD
ICE PRESENT?
YES
NO
$K_{DP} \geq 0.3$ and $Z_H \geq 35$?
YES
R = R(K_{DP})
NO
$Z_H \neq$ BAD?
YES
R = R(Z_H^{RAIN})
NO
R=BAD
$K_{DP} \geq 0.3°$,
$Z_H \geq 35.0$ dBZ
$Z_{DR} \geq 0.5$ dB?
NO
YES
ZH > 30 dBZ,
$Z_{DR} \geq 0.5$ dB?
NO
YES
R = R(Z_H)
R = R(Z_H,Z_{DR})
(1) R(K_{DP},Z_{DR})
(2) R(K_{DP})
(3) R(Z_H,Z_{DR})
R > 50 mm/hr, dBZ > 50 ,or
Z, ZDR corr. too large ?
YES
R = R(K_{DP})
no
KDP ≥ 0.5?
YES
R =R(K_{DP},Z_{DR})
no
KDP< 0.5?
YES
R =R(Z_H,Z_{DR})
ARMOR
HYBRID
RAIN RATE
ALGORITHM
1-hr
Accumulation
6-hr (N-hr)
Accumulation

AREPS Coverage



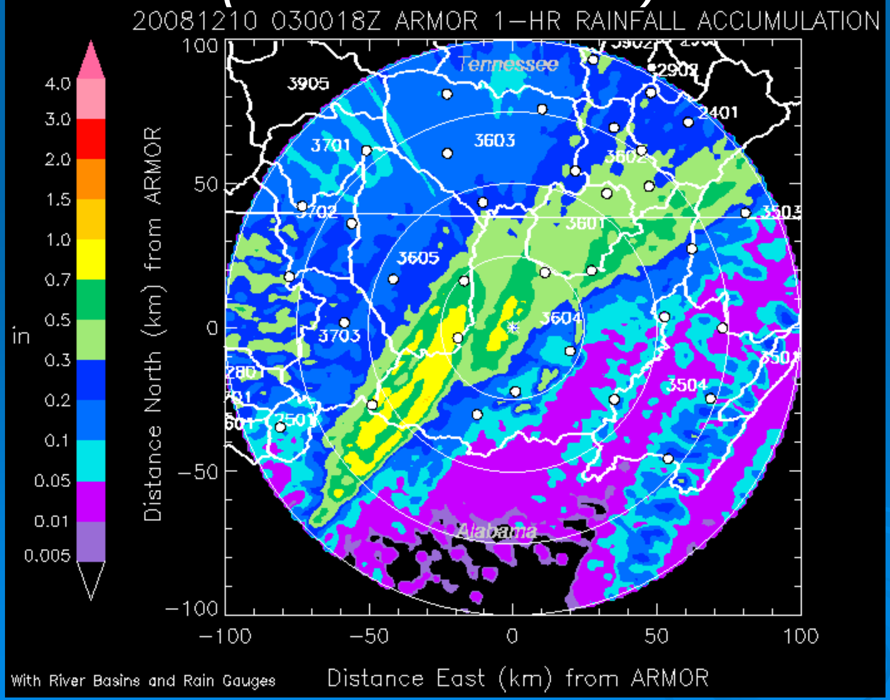
- 100 km from ARMOR (HSV)
- 11 sub-basins
- 42 rain gauges

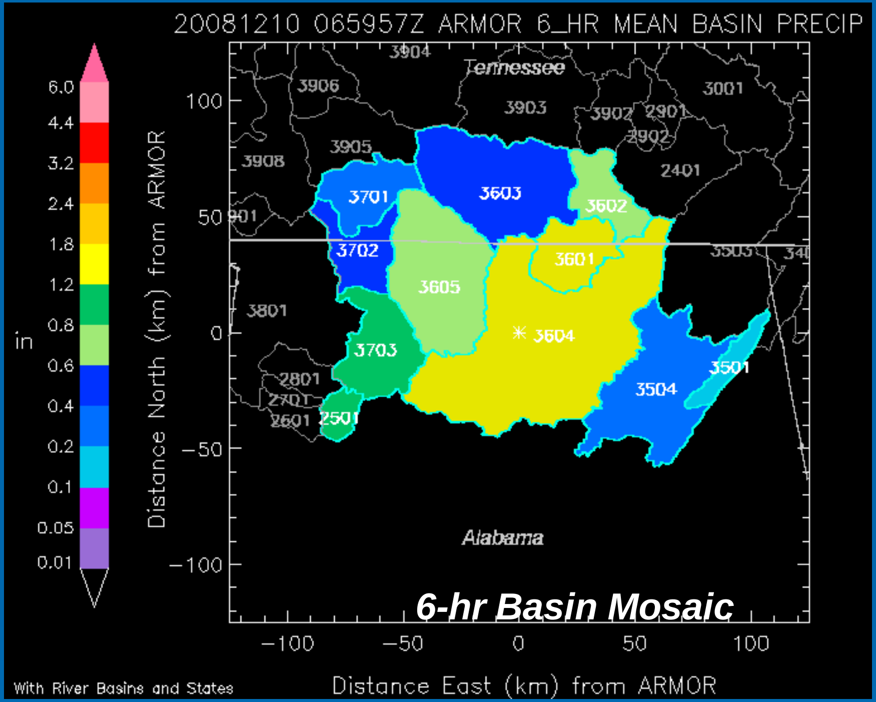
AREPS Distributed Rainfall Products

http://vortex.nsstc.uah.edu/armor/webimage

- Rainfall products created every 5-min:
  - 1-hr and 6-hr basin/sub-basin rainfall statistics (mean, max, min, etc)
  - Rainfall at critical locations (e.g., dams)
  - rainfall accumulation images (1-hr, 6-hr)
- Text files transmitted every hour to TVA
  - Contain previous hour's rainfall
  - used as input by inflow model input

1-hr rainfall (also create 6-hr rainfall)





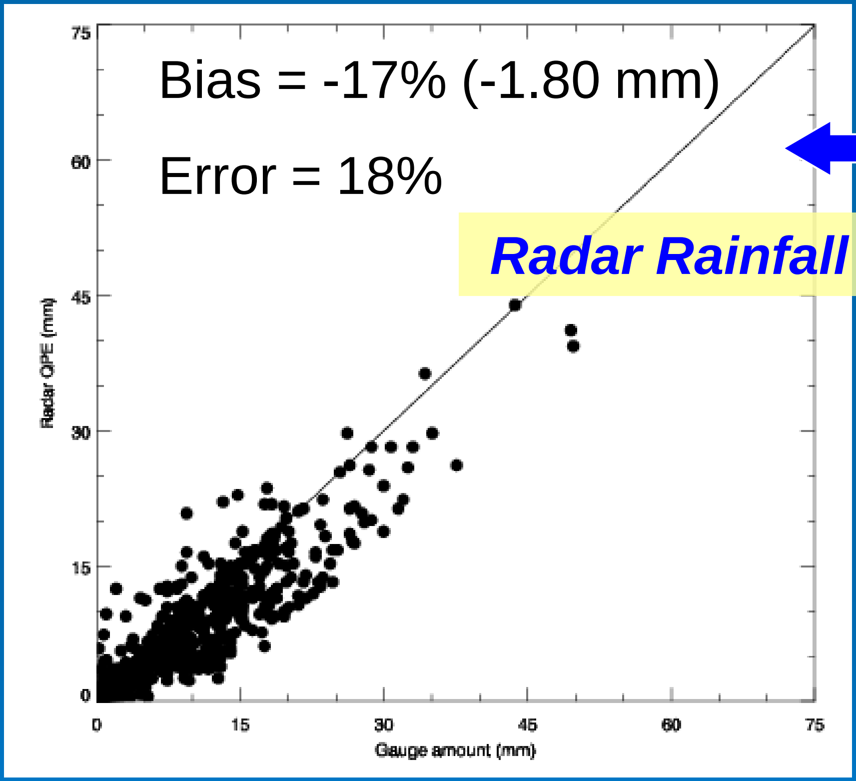
6-hour accumulation statistics

TVA Basin: 6-HR Rain stats (inches): 100 km Radius from ARMOR
Date/Time (UTC): 20081210_065957

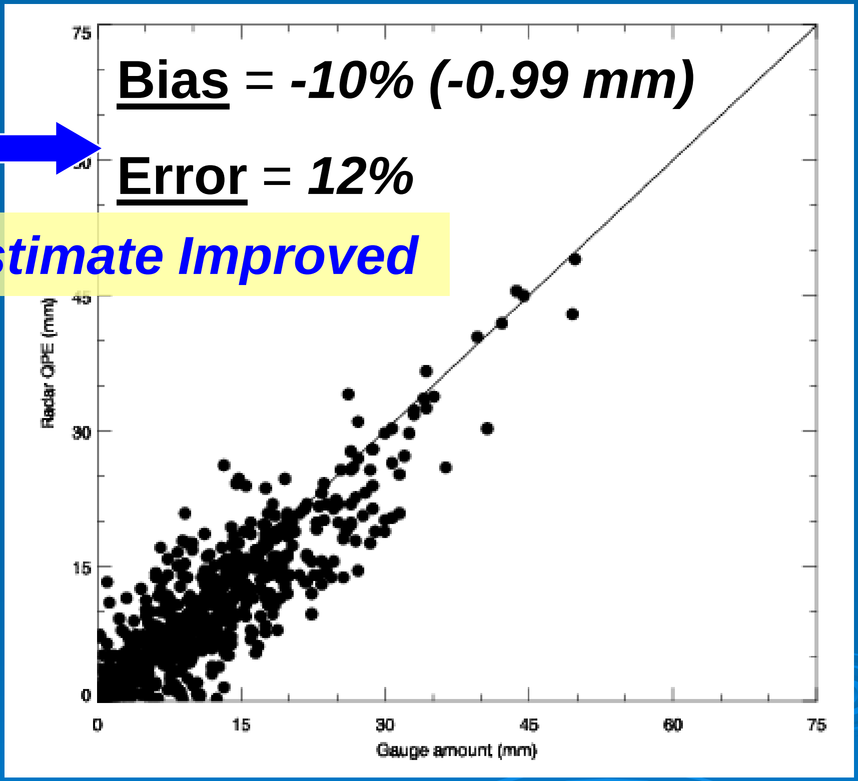
Bsn#	Mean	Max	Min	S-Dev	% RPxl
3603	0.434	0.875	0.139	0.529	100.000
3602	0.789	1.523	0.299	2.050	100.000
3701	0.351	0.616	0.004	0.850	99.112
3605	0.778	1.969	0.189	1.046	100.000
3702	0.472	0.904	0.009	1.167	100.000
3601	1.245	2.004	0.468	3.096	100.000
3604	1.246	2.488	0.196	0.522	100.000
3703	0.957	1.727	0.382	1.842	100.000
3504	0.239	1.138	0.057	0.320	100.000
3501	0.120	0.349	0.000	0.434	87.500
2501	1.040	1.466	0.609	4.445	100.000

Verification: Point Comparisons
AREPS vs. TVA rain gauges
(October 2007 – June 2008)

Before Calibration Correction



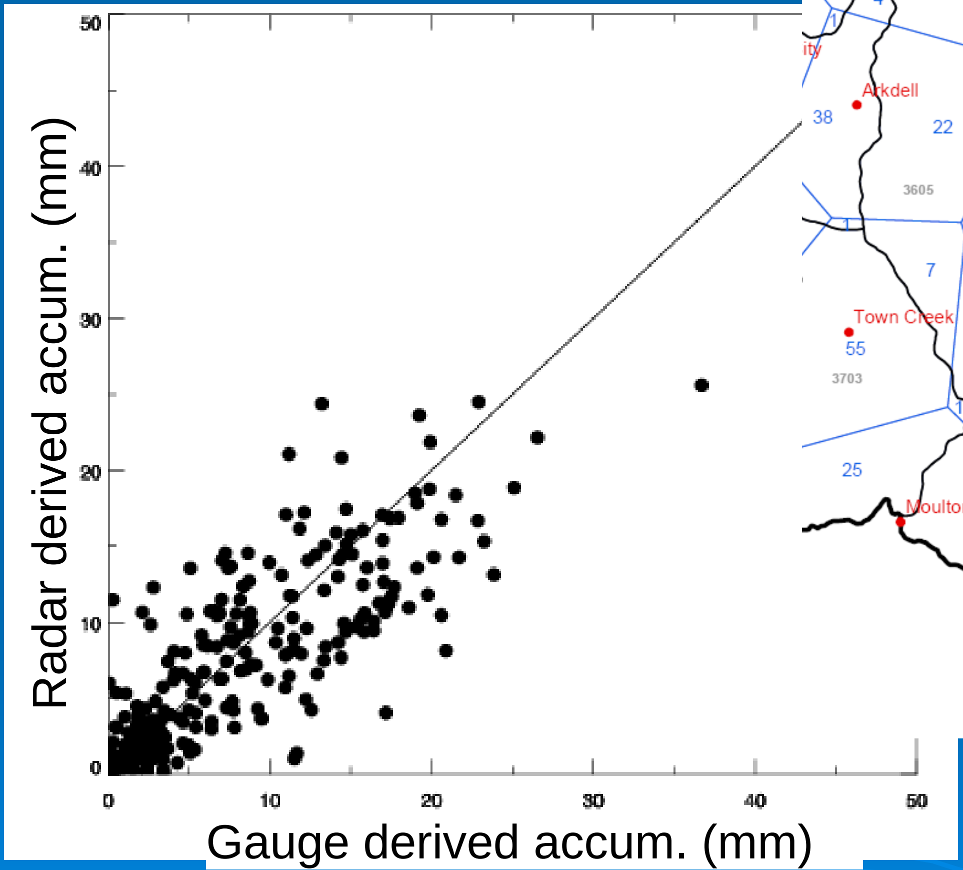
After Correction

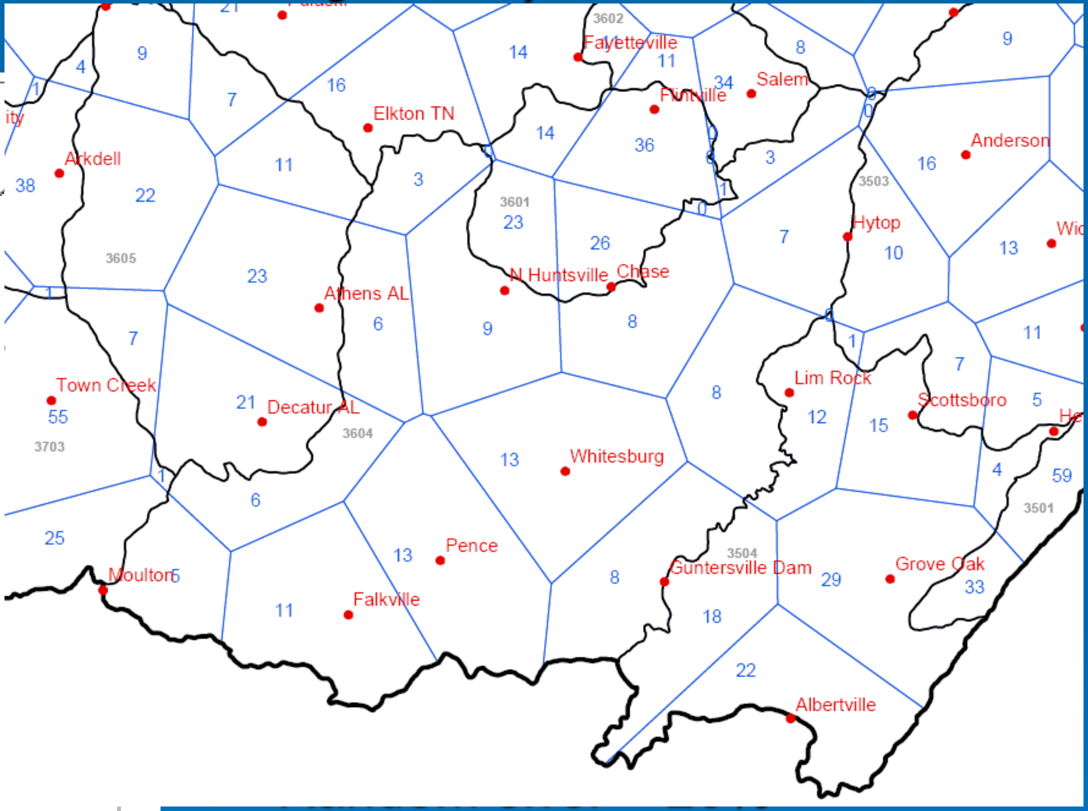


Radar Rainfall Estimate Improved

- **Original bias and error targets achieved (+/-20%, +/-25% respectively)**
- **Constant monitoring of calibration maintains precision and accuracy of product**

Verification: Sub-basins
AREPS vs. rain gauge-derived areal mean
(January 2008 – July 2008)

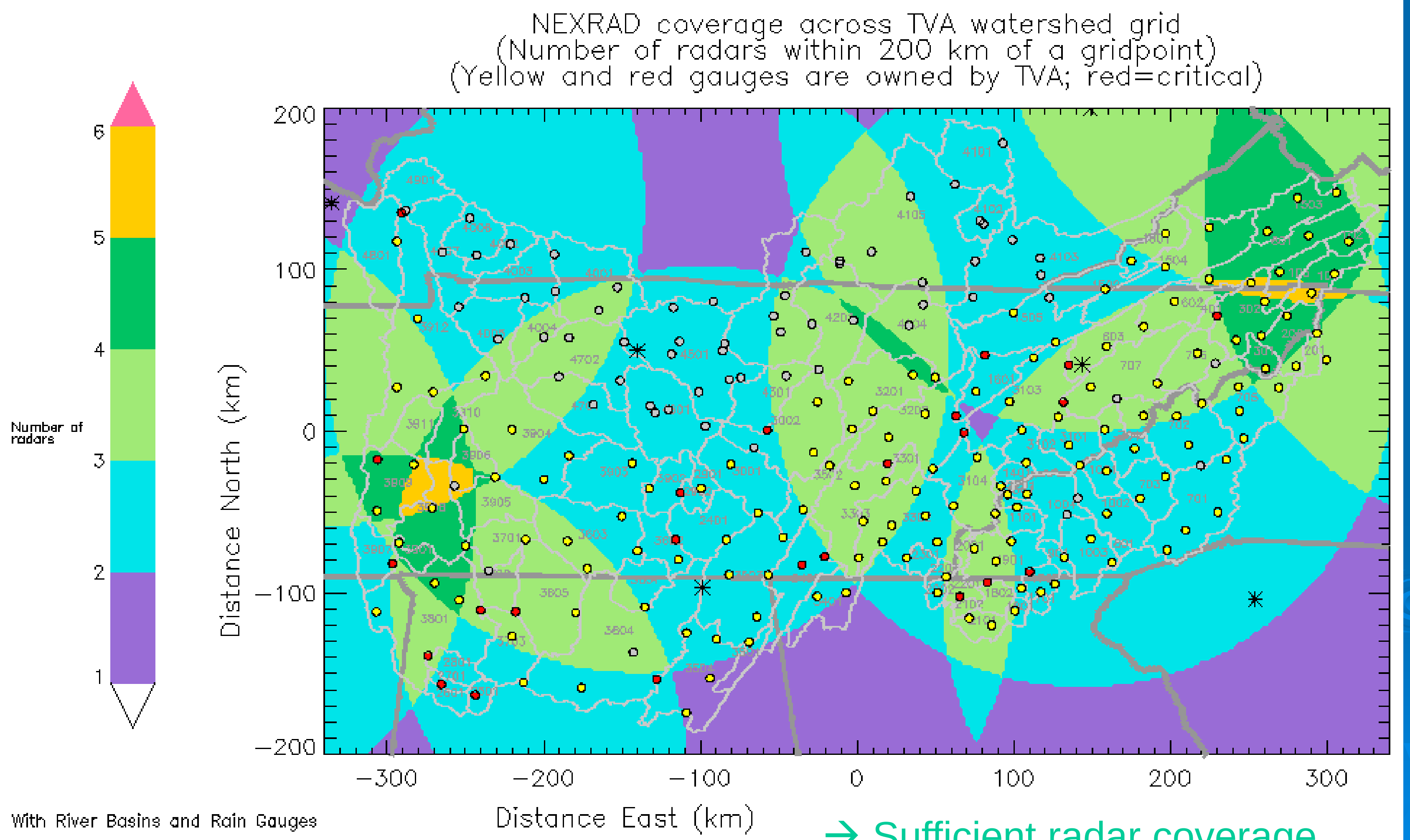




- Largely attributed to Theissen polygons (i.e, density of rain gauge network with respect to sub-basin boundaries)

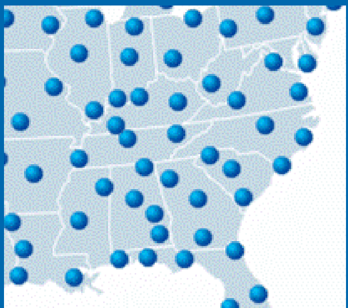
→ ***Demonstration successful….but what about the rest of the watershed?***

Expansion of radar rainfall maps across entire TN River watershed



→ Sufficient radar coverage

NEXRAD Rainfall Estimation Processing System (NREPS)



WSR-88D Level II

Unidata LDM (IDD)

NREPS

1) Time matching

2) QC/rain rate algorithm

- AP, Sun strobe removal
- C-S partitioning (37 dBZ)
- $Z - R$ relation
- Melting level correction

3) Gridding 2 km²

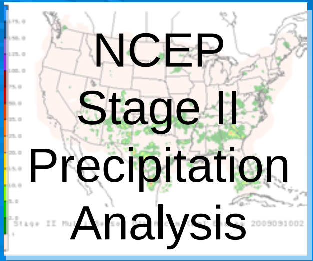
4) Merge radars

5) Hourly accumulation

HRAP 2 NREPS

FTP

LDM outage



NREPS Processing

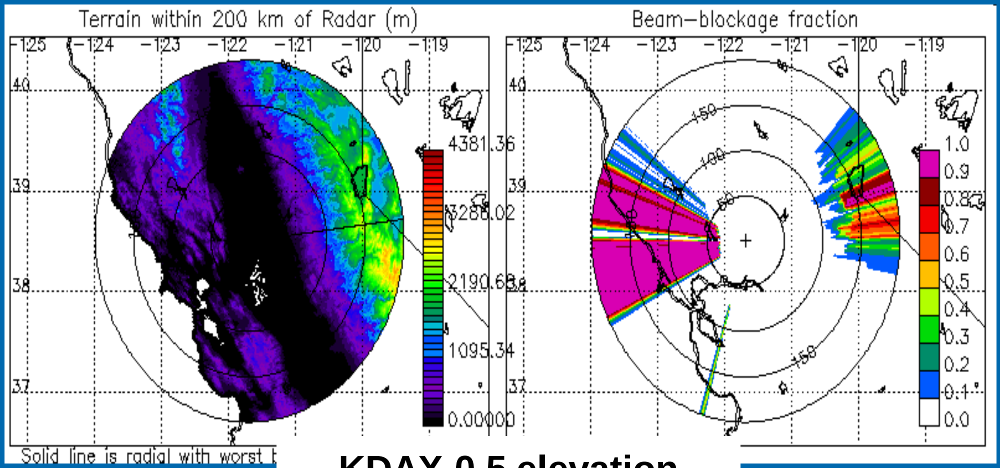
- VCP-based sweep selection (e.g., 1st SUR and Doppler scans of each elevation)
- Beam blockage correction for occultation
- Clutter mitigation (NEXRAD ORPG 3)
  - Notch width filter
  - Sun strobe removal
- Non-precipitation mitigation (Steiner and Smith 2002)
  - Vertical extent and structure
  - Spatial variability
- Additional checks using VCP mode and RUC analysis melting level
  - Clear-air VCP + 0°C height > 100 m → no precipitation
  - Clear-air VCP + 0°C height ≤ 100 m → snow
- Rainfall from individual radar interpolated to 2 km x 2 km Cartesian grids using NCAR reorder at 1.0, 1.5 and 2.0 km ARL for TVA (more vertical levels every 0.5 km for CA domain).
  - Use lowest available "good" rainfall rate for each radar grid point
  - Individual radar grids are composited to a single mosaic using an inverse exponential weighting

Beam Blockage Correction

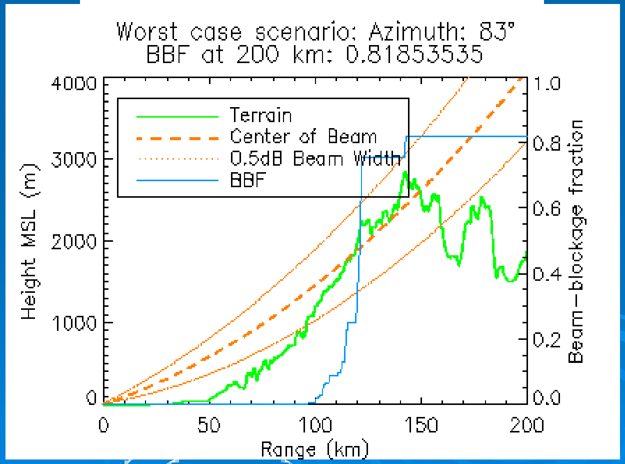
- DEM vs ray path model → regions of occultation
- Visibility correction factor (Germann et al. 2006)

  $f = (1\text{-}blockage)^{-1}$

- Adjust reflectivity field for blockage of 5% to 90% (Lang et al. 2009)

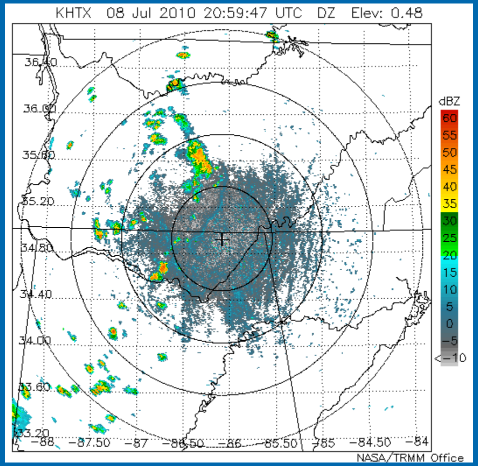


KDAX 0.5 elevation

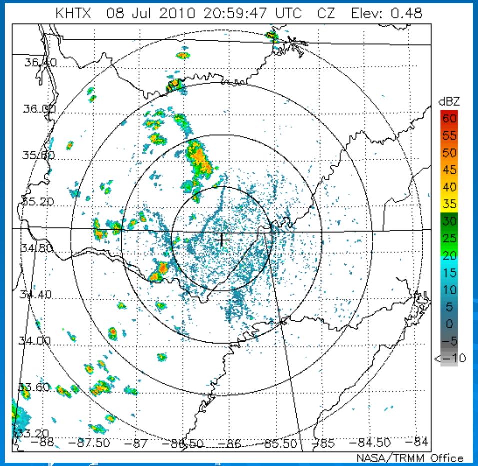


Non-precipitation mitigation

- Steiner and Smith (2002)
- Reduce AP
- Decision tree methodology performed in polar coordinates
  1. ECHOtop → echoes separated from precip
  2. SPINchange → echoes embedded in precip
  3. vertGRAD → limits echo removal around edges of storm cells
- Computationally fast and efficient
- Difficulties with widespread clear-air echoes

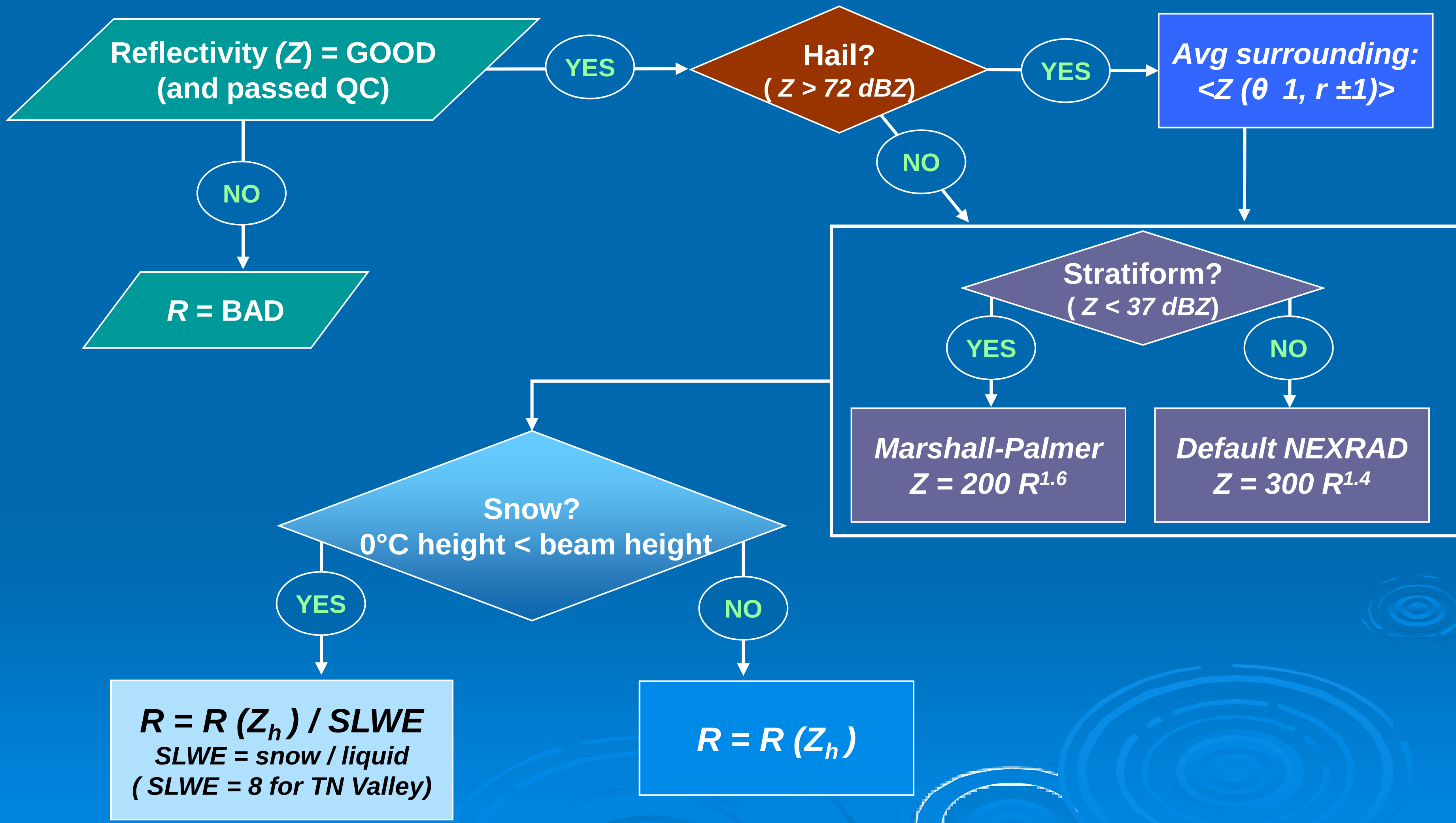


BEFORE



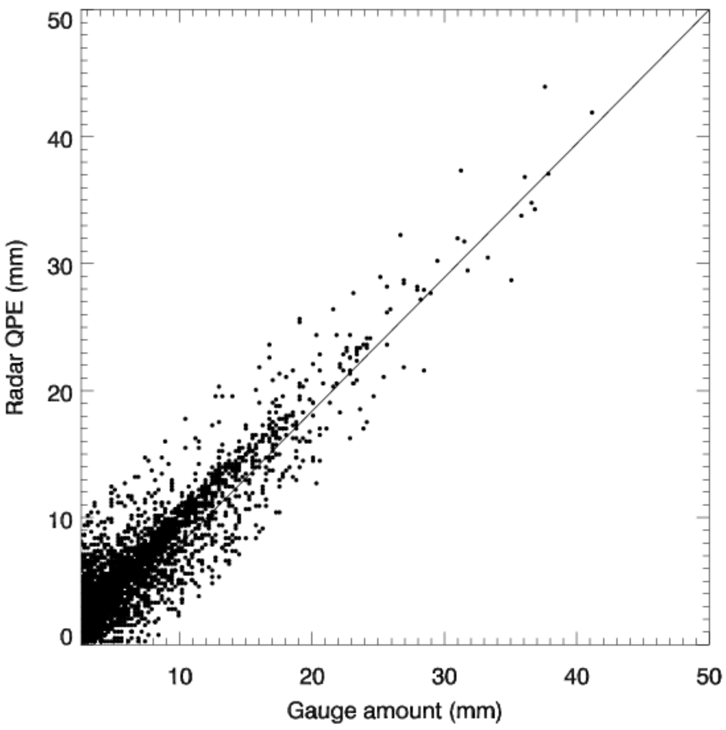
AFTER

NREPS Rain Rate Algorithm



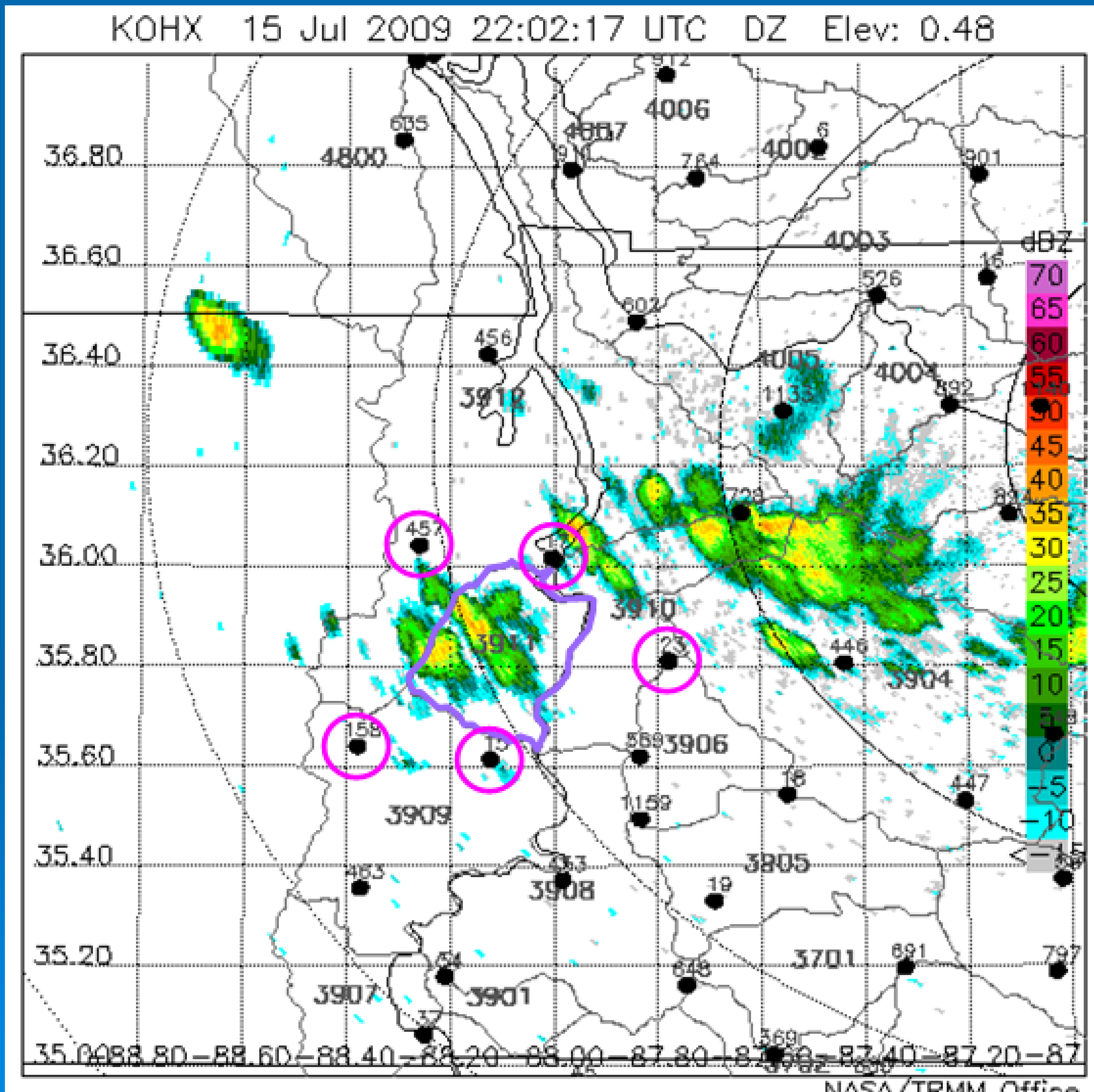
NREPS Performance

<u>*NREPS vs Rain Gauges*</u>
1-HR Rainfall
March – May 2009



- Error = 20%
- Bias = -7%
- *R^2 = 0.93*
- NREPS has been implemented by TVA
  - used routinely in river scheduling operations
- TVA rain gauge removal
  - Gauges selected after extended NREPS validation
  - 18 gauges removed thus far
  - Additional gauges (TBD) next year

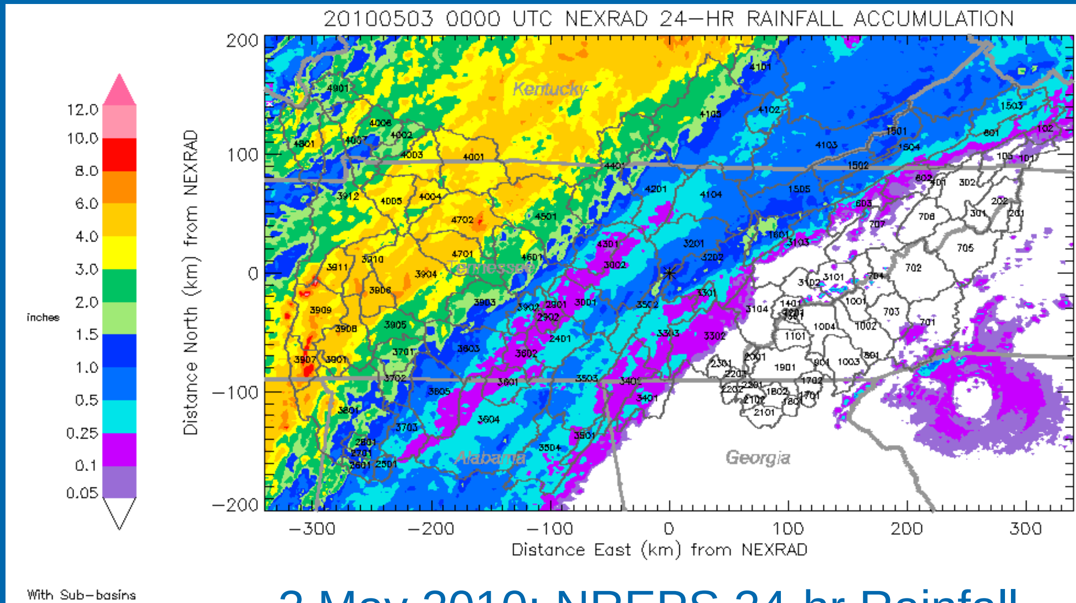
Coverage: Radar vs Rain gauge



- Intense isolated rainfall in west-central TN (sub-basin 3911)
- Amounts: (6pm-midnight)
  - Gauge = 38.1 mm (1.5 in)
  - Radar = 125 mm (4.9 in)
- Which was right ?
  - radar beam < melting level
  - max reflectivity < 50 dBZ
  - stationary thunderstorm
  - no rain gauges in 3911

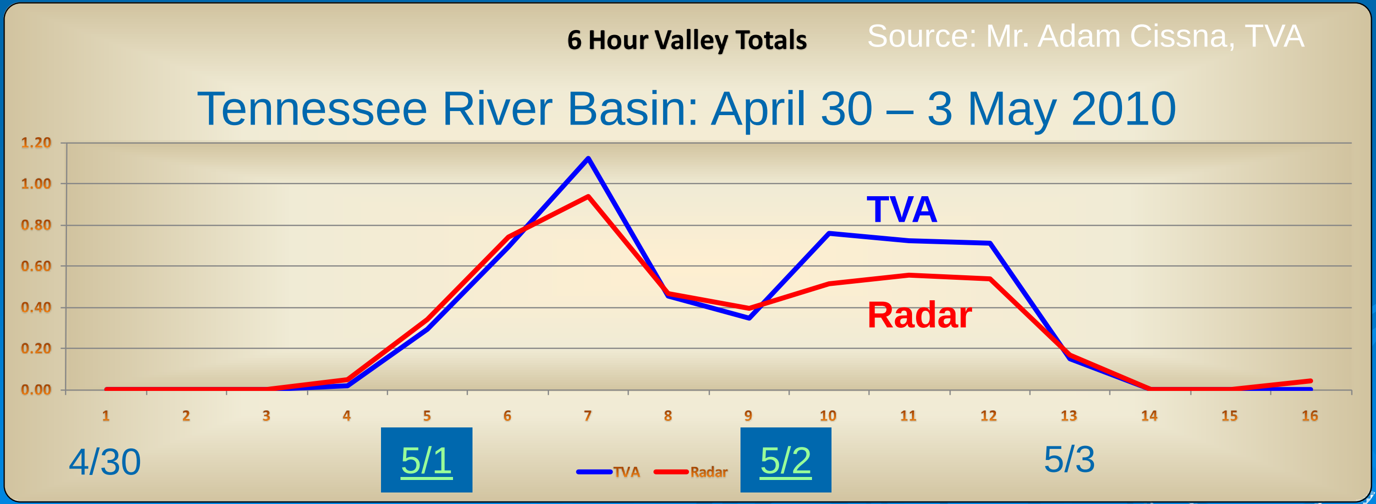
→ Advantage: Radar

May 2010 “1000-year flood” in Middle and West Tennessee



2 May 2010: NREPS 24-hr Rainfall

Downtown Nashville TN flooding, especially near Cumberland River, which crested at 52 ft there, and tributaries.



6-HR Basin Mean

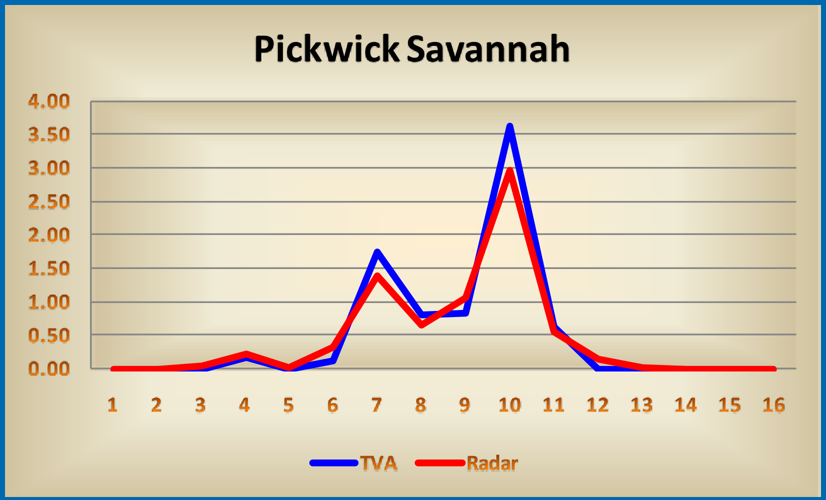
6-hour periods (Daily quarters)

TVA: Gauges with Theissen polygons to-sub-basin 6-hr mean to basin mean

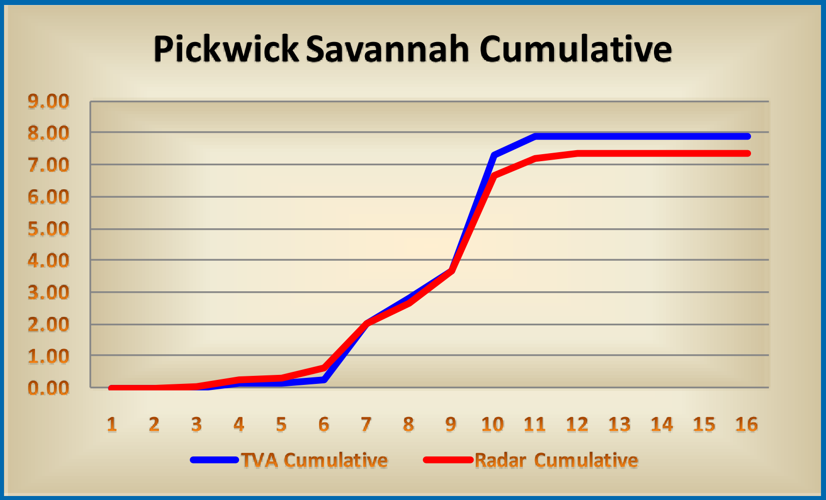
Radar: NREPS grids to sub-basin 6-hr means to basin mean.

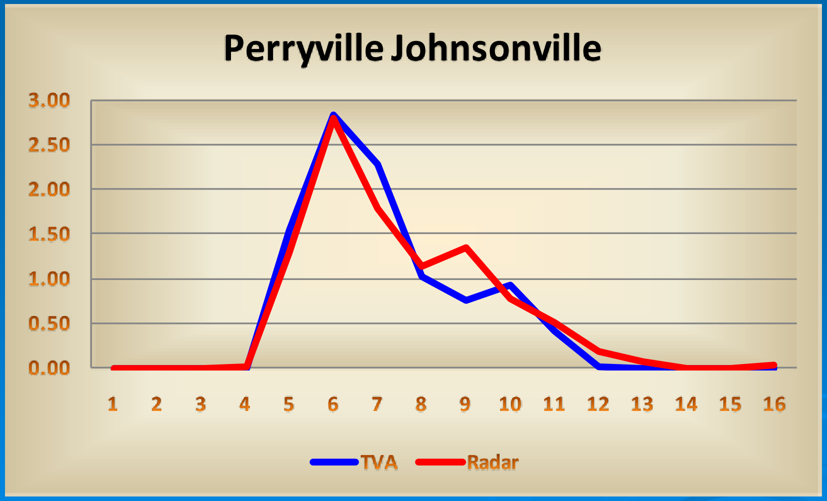
In many sub-basins, there is good agreement between TVA-gauge and NREPS 6-HR cumulative rainfall.

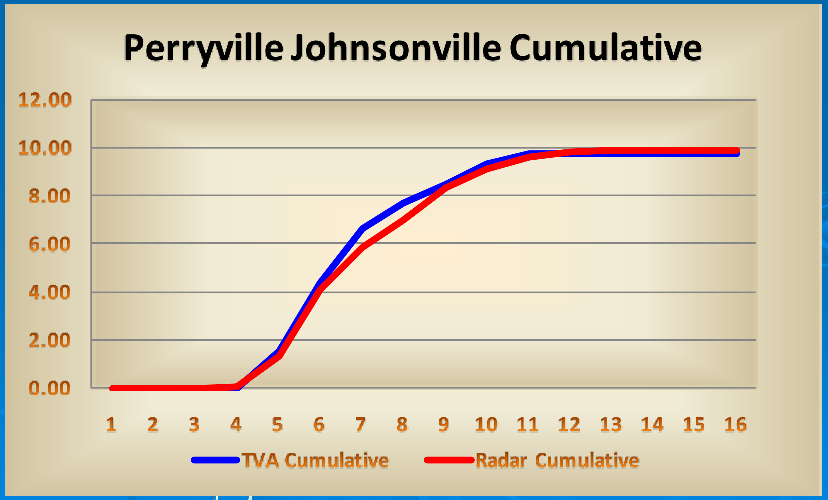
Sub-basin 6-HR Rainfall



Sub-basin Cumulative Event Rainfall





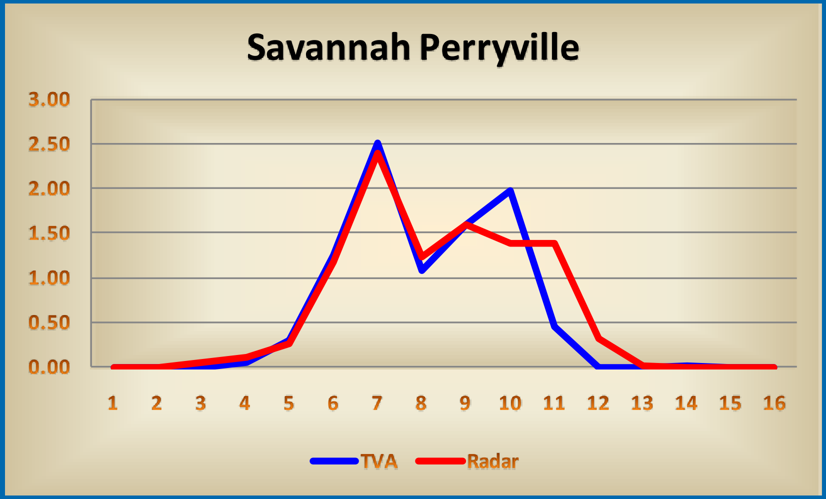


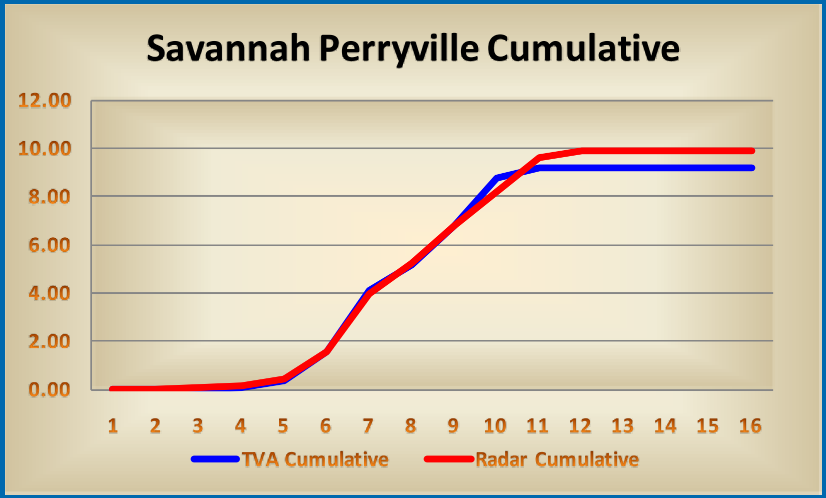
Figures are courtesy of Mr. Adam Cissna, TVA

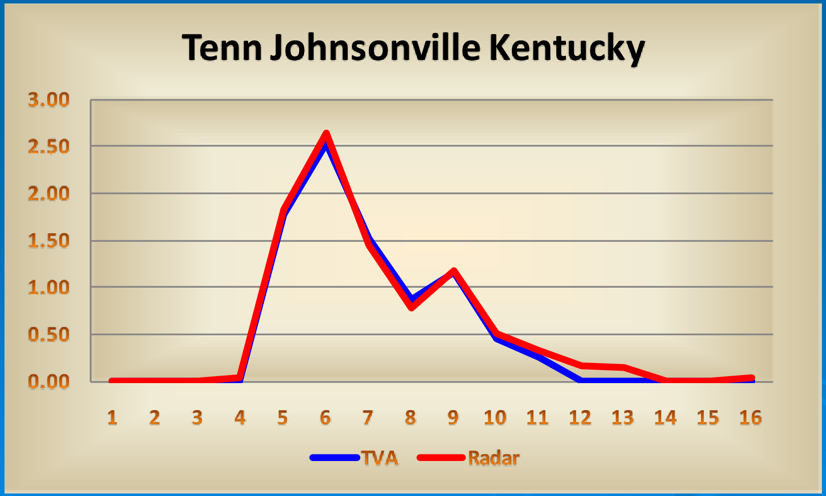
More good agreement…

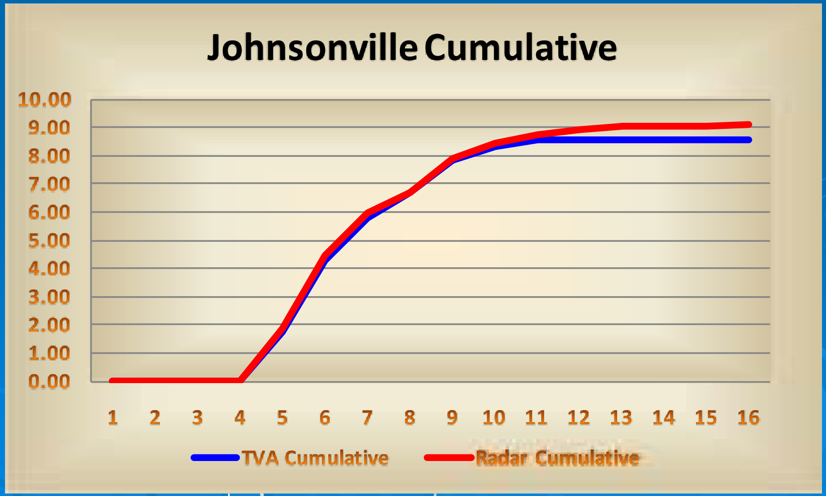
Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall







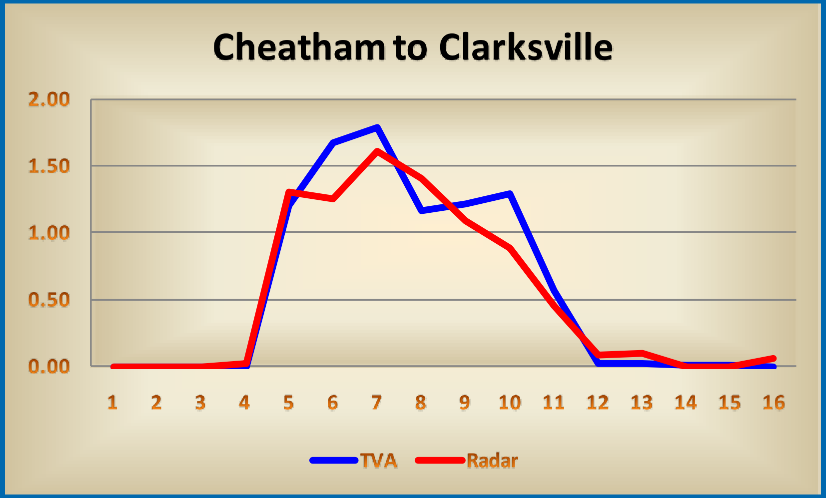


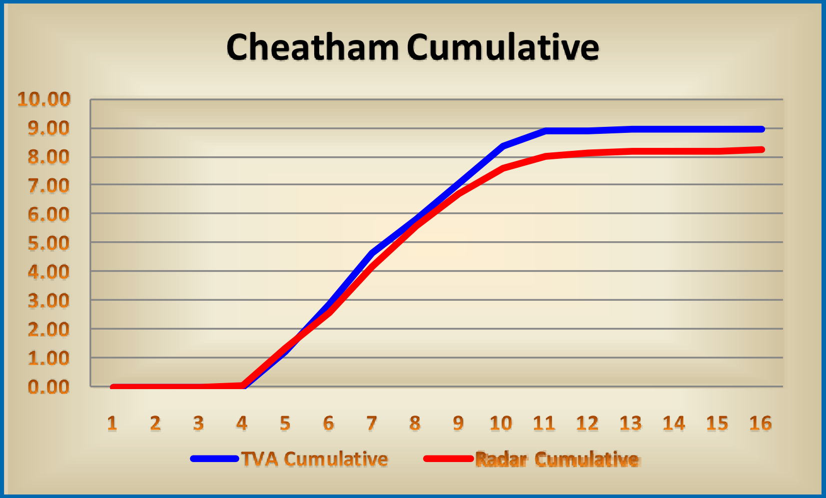
Figures are courtesy of Mr. Adam Cissna, TVA

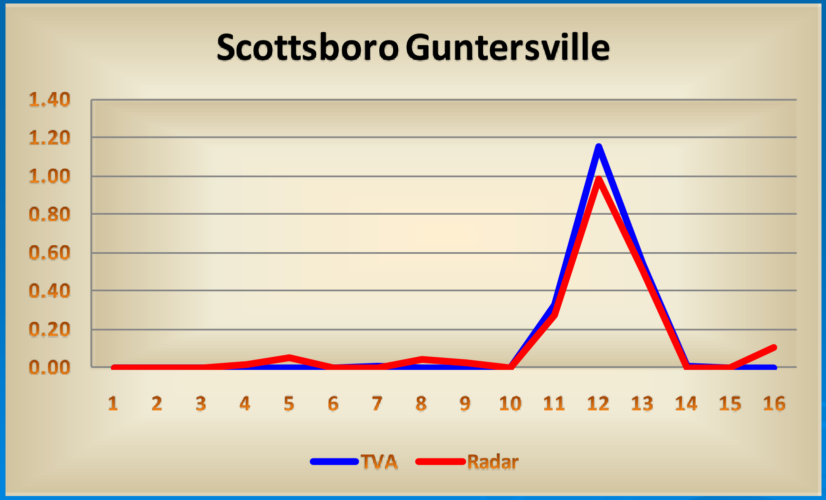
And some more (including one with less rain)…

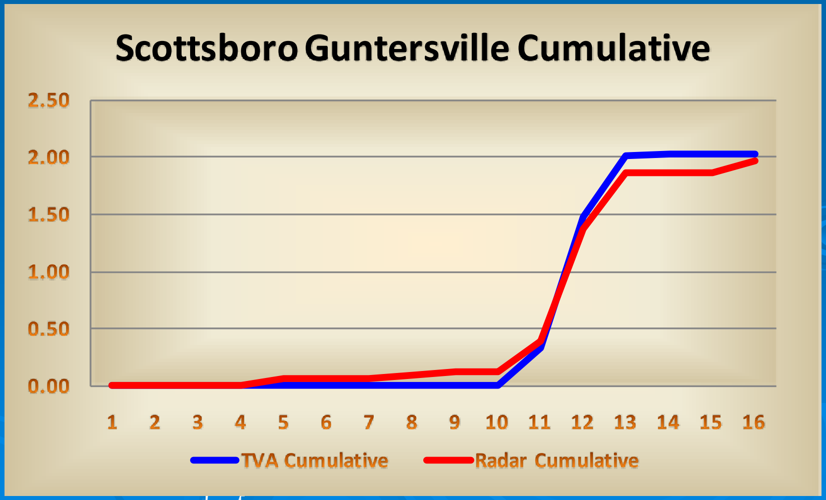
Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall







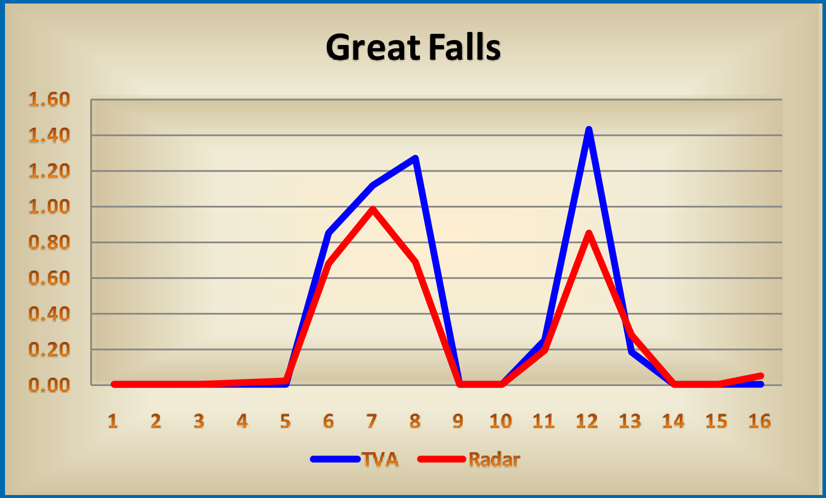


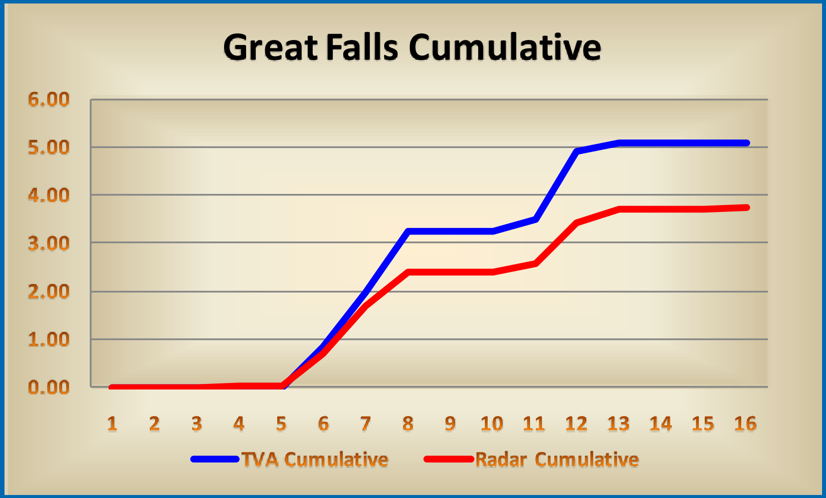
Figures are courtesy of Mr. Adam Cissna, TVA

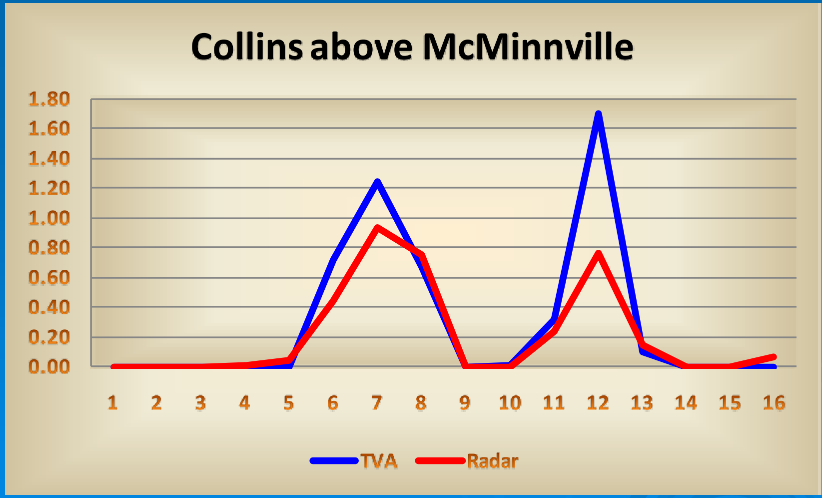
But, as seen in the Basin mean, there was a tendency for the radar < gauge rainfall in some sub-basins, especially in "2nd wave" of heavy rain on May 2nd.

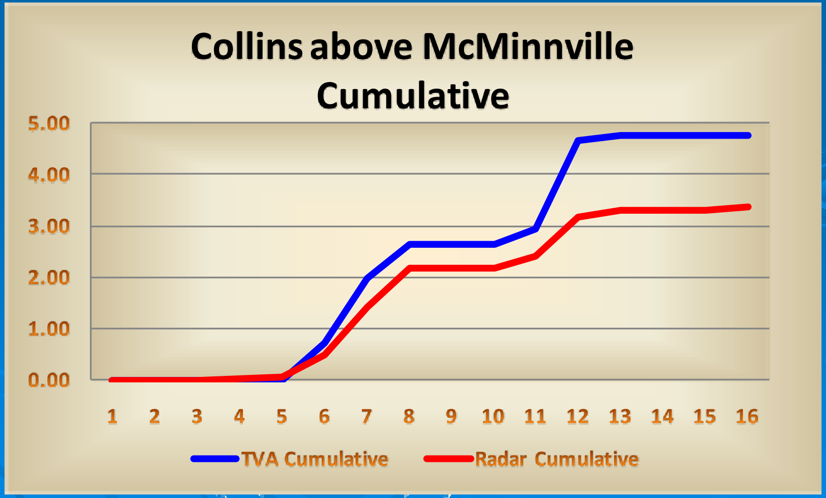
Sub-basin 6-HR Rainfall

Sub-basin Cumulative Event Rainfall





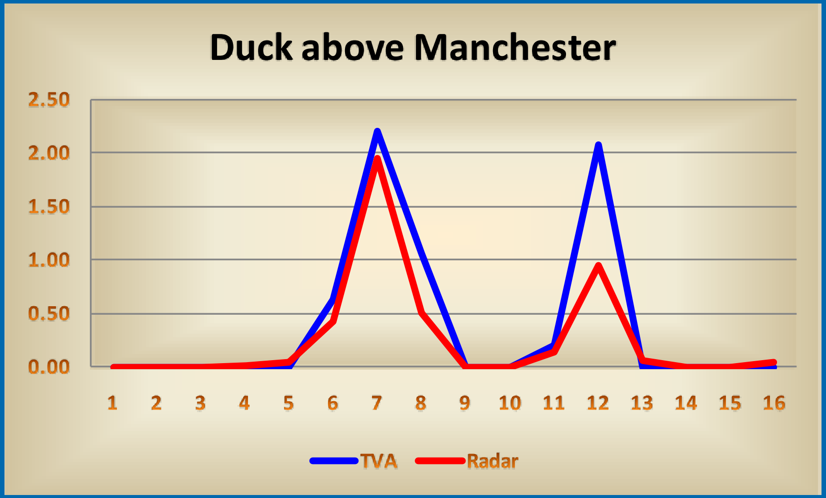


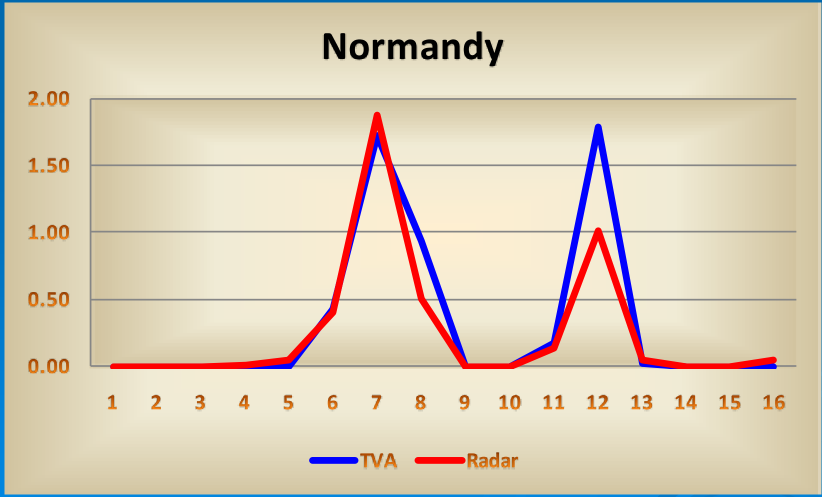


Courtesy Mr. Adam Cissna, TVA

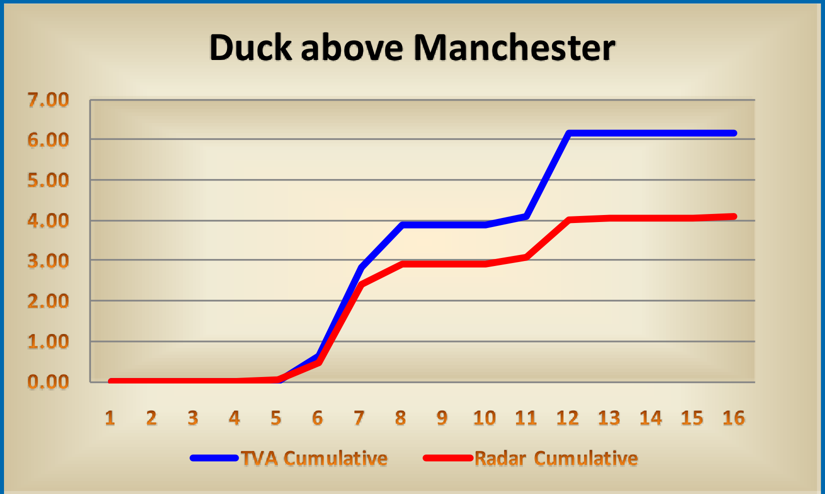
Some more sub-basins with radar < gauge in 2nd peak...

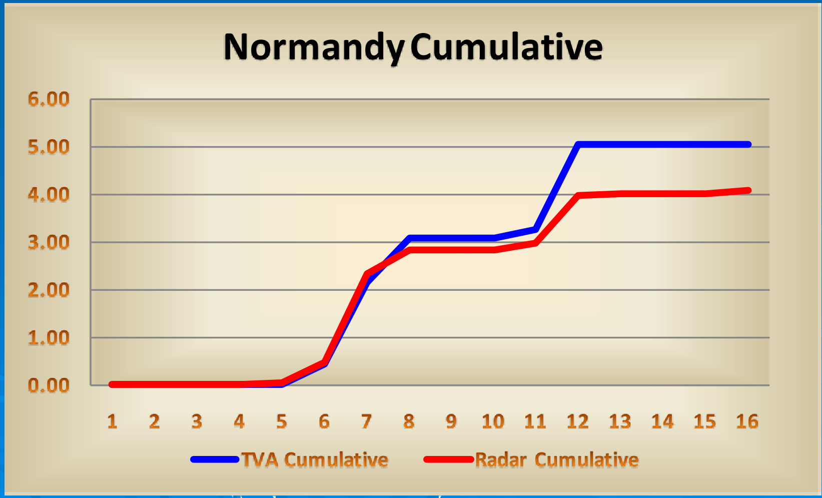
Sub-basin 6-HR Rainfall





Sub-basin Cumulative Event Rainfall

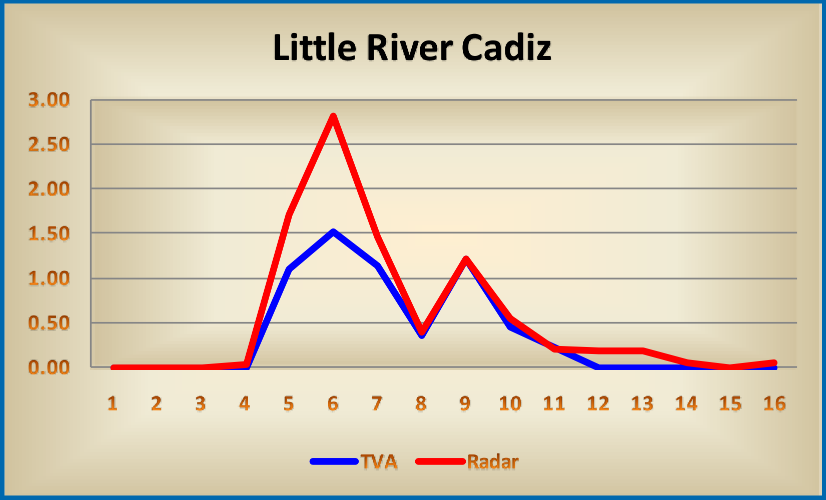


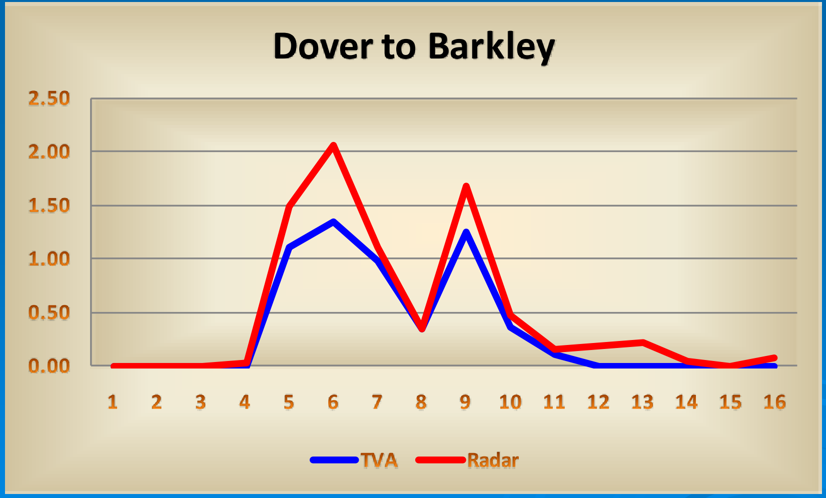


Figures are courtesy of Mr. Adam Cissna, TVA

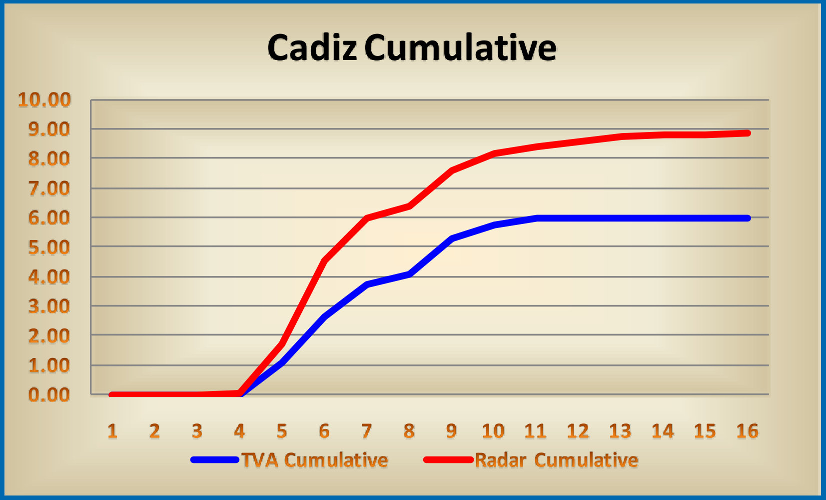
And there are almost always a couple of exceptions to the rule!
Radar > gauge, especially in the 1st wave of heavy rain on May 1st.

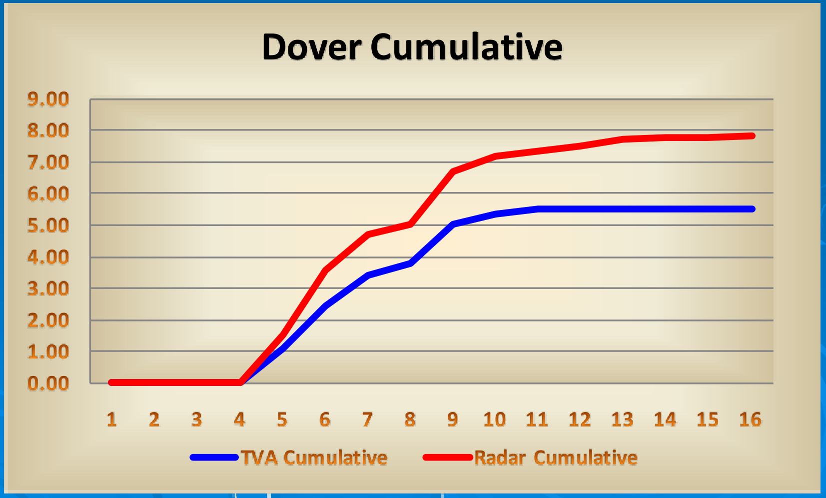
Sub-basin 6-HR Rainfall





Sub-basin Cumulative Event Rainfall

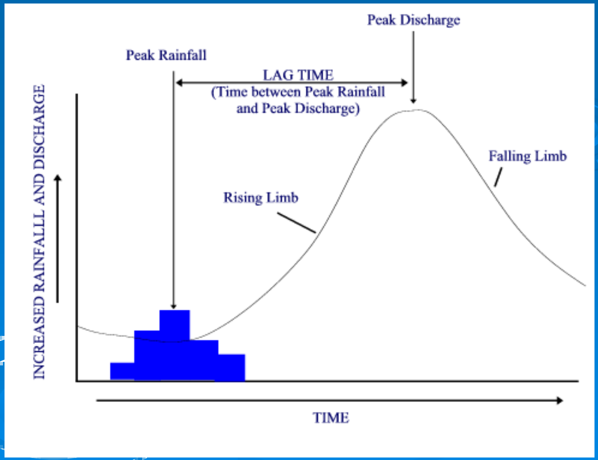




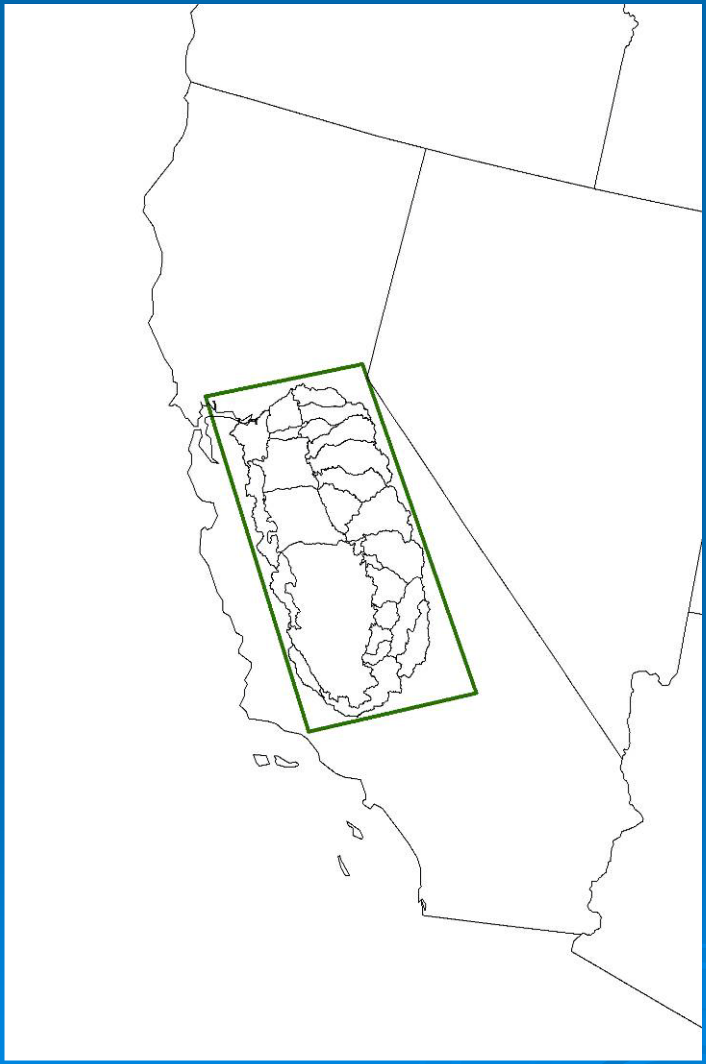
Courtesy Mr. Adam Cissna, TVA

TVA-VCSI Project Practical Experience

- Detailed developer (user) knowledge of user requirements, priorities and computing environment (tool capabilities and limitations) is key.
  - With diverse backgrounds, takes time and committed project team to develop productive communication and working relationship to solve complex issues.
  - Active user participation in system testing and improvement is very helpful.
- In an operational hydrological setting like the TVA River Forecast Center, rainfall **data availability** is the primary priority.
- Implications for robustness of
  - WSR-88D data pathways (Internet and LDM stability, back-up),
  - Software design (exception handling, stability, quality assurance)
  - Hardware design (memory, CPU and storage specifications to worst case scenarios; redundant systems)
- Data accuracy is important but secondary.
  - Because of river management complexity and model uncertainty, it is difficult for TVA to provide 6-hr sub-basin rainfall accuracy guidelines.
  - Forecasters manually adjust model hydrographs to stream flow gauge data in real time. Model output is tuned to measured river response.



California Water Resources Project

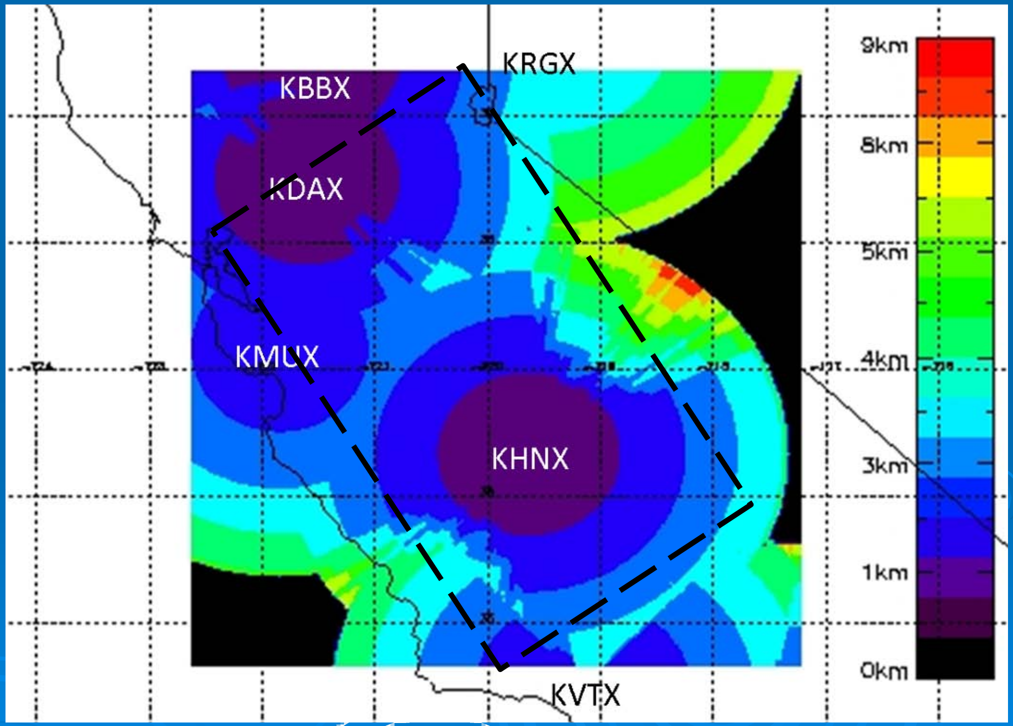


- Funded by NASA through American Reinvestment & Recovery Act
  - Through June 2011
- Develop integrated tool to assist water management within the San Joaquin River Valley
  - Radar precip estimates
  - Distributed hydro model
  - Snowfall measurements
  - Surface temp / moisture
- NREPS was selected to provide precip component

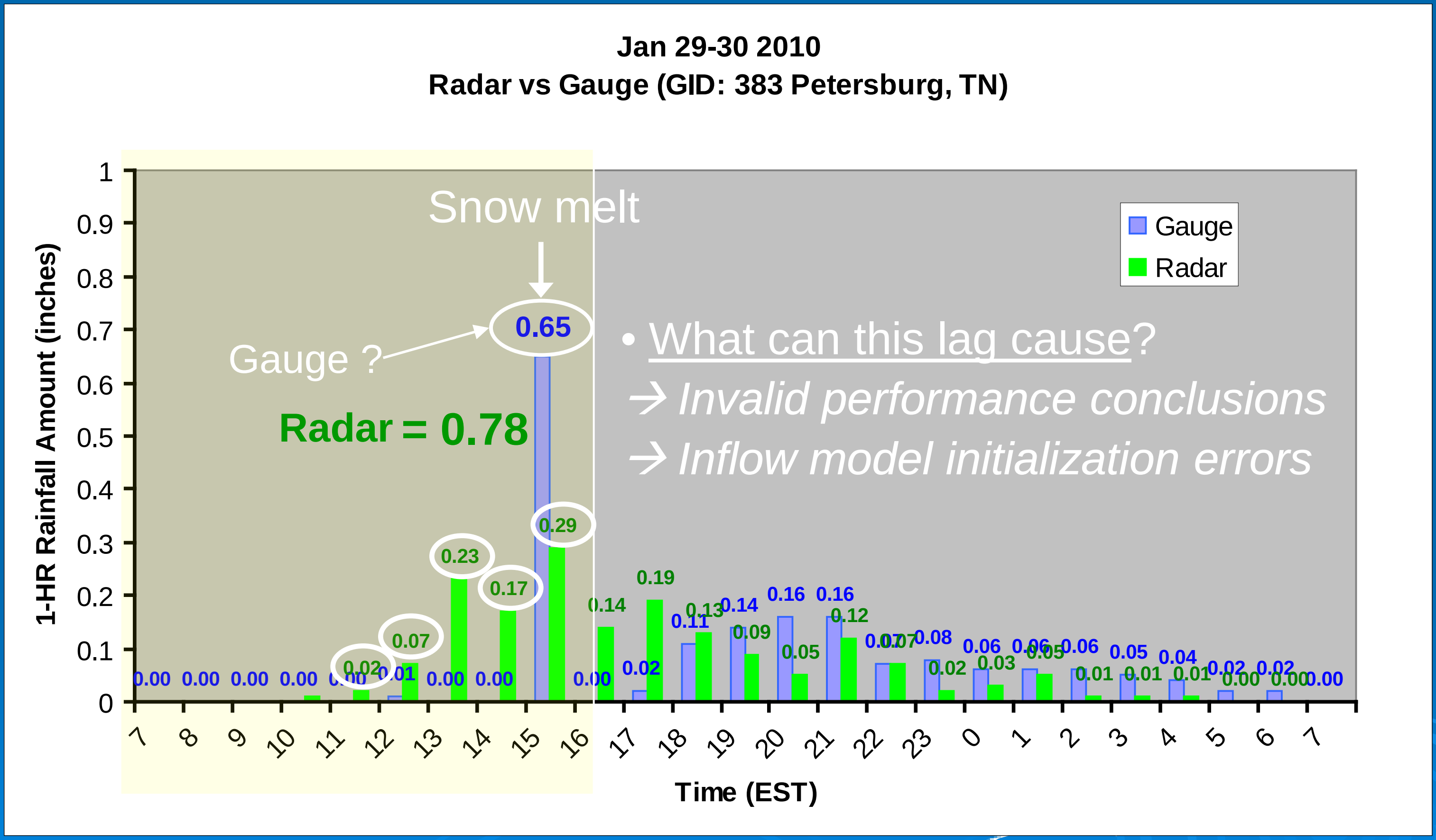
Challenges

- Residual non-precip contamination
- Nature of precipitation
  - Shallow, non-bright brand
  - Snow vs rain
- Terrain and remaining occultation
  - Non-standard refraction
- Beam height vs melting level

Map of lowest usable beam height in Central CA



Radar vs rain gauge comparison during mixed-precip events



Future NREPS plans

- Vertical profile of reflectivity (bright band mitigation, ice vs. rain, rain rate vs. beam height)
- Explore more sophisticated precipitation type (C/S) identification methodology
  - Other categories for Coastal California – shallow, non-convective, non-bright band ?
  - z-R's for the appropriate regime and precipitation type
- For CA ARRA NREPS: Integration with NASA distributed hydrologic model for soil moisture and evapo-transpiration estimates
- Back to the future – As WSR-88D network is polarized, transition z-R algorithm to dual-polarization hybrid R[Z,Zdr,Kdp] methodology at S-band?